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AIR FORCE INSTITUTE OF TECHNOLOGY

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UNITED STATES AIR FORCE

AN ATTEMPT TO MODEL THE GUN
INTERNAL BALLISTICS PROBLEM

THESIS

AM/ME/72-2 James Frederick Setchell
Captain USAF

SCHOOL OF ENGINEERING

86

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Institute of Technology Wright-Patterson Air Force Base, Ohio	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

AN ATTEMPT TO MODEL THE GUN INTERNAL BALLISTICS PROBLEM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

AFIT Thesis

5. AUTHOR(S) (First name, middle initial, last name)

James F. Setchell, Jr.
Captain USAF

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1972	74	7

8a. CONTRACT OR GRANT NO. b. PROJECT NO. N/A c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) GAM/ME/72-2 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

Approved for public release; IAW AFR 190-17 Stephen B. Ingram, Captain, USAF Director of Information, AFIT	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

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DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gun Internal Ballistics						

GAM/ME/72-2

AN ATTEMPT TO MODEL THE GUN INTERNAL BALLISTICS PROBLEM

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Captain USAF

Graduate Aerospace-Mechanical Engineering

March 1972

Preface

In this work I have made an effort to model the complex power-burning, chambered-gun internal ballistics process with an artificial sequence of fundamental processes. Although I was unable to obtain acceptable results from the model in the time allotted for this work, I feel that the partial results attained to date indicate that the model shows good promise. At the very least I have learned a great deal about the gun business, the application of engineering principles to physical problems, the value and results of simplifying assumptions, and the frustrations involved in creating and perfecting a lengthy and involved computer program.

I now take this opportunity to express my gratitude to my thesis advisor, Dr. James Hitchcock, both for posing this most challenging problem as well as for his knowledgable advice on analyzing the gun problem. I am also grateful for the timely suggestions made by the other gentlemen on my thesis committee, Dr. Andrew Shine and Capt (Dr.) Stephen Koob. And I thank my lovely wife Judy, whose patient understanding during this difficult time has been truly remarkable.

James F. Setchell

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List of Symbols

Latin Symbol

a	Acceleration	ft/sec^2
A	Area	in^2
b	Covolume	in^3/lbm
C_d	Drag Coefficient	
C_v	Constant Volume Specific Heat	Btu/lbm R
D	Drag	lbf
f	Force	lbf
F	Gun Force Constant	Btu/lbm
K_e	Erosive Burn Constant	
L	Length	in
M	Mass	lbm
N	Number of grains/segment	
P	Pressure	lbf/in^2
q	Heat Energy Released by Propellant per Unit of Mass	Btu/lbm
Q	Heat Energy Released by Propellant	Btu
R	Propellant Grain Burn Radius	in
$\dot{R}$	Propellant Grain Burn Rate	in/sec
R_g	Propellant Gas Constant	Btu/lbm R
t	Time	sec
T_{iso}	Isochoric Flame Temperature	R
T	Temperature	R
u	Internal Energy per Unit of Mass	Btu/lbm
U	Internal Energy	Btu

Latin Symbol

v	Velocity	ft/sec
V	Volume	cub in

Greek Symbols

β	Burn Rate at 1000 psia	in/sec
η	Burn Rate Exponent	
γ	Ratio of Specific Heats	
ρ	Density	lbm/in^3

Abstract

An attempt is made to model the internal ballistics process of a powder-burning gun by replacing the actual internal ballistics process with an incremental sequence of phases. These phases are a constant-volume energy transfer phase, a shell motion and finite-amplitude wave propagation phase, a propellant motion phase, and a gas expansion and mass transfer phase. The model permits consideration of a chambered, powder-burning gun problem with unspecified pressure, density, velocity, temperature, and propellant distributions. The method of solution shows promise, but useful results have not been attained to date.

AN ATTEMPT TO MODEL THE GUN INTERNAL BALLISTICS PROBLEM

I. Introduction

Background

Gun internal ballistics is the study of the conversion of latent chemical energy of a propellant to kinetic energy of a projectile. It is only concerned with the period of time that begins with propellant ignition and ends with the projectile leaving the barrel. The primary purpose of a gun internal ballistics study is to predict the gas property and shell motion history of a gun.

The formal study of gun internal ballistics began during the eighteenth century with the work of Benjamin Robins in 1742 and Count Joseph-Louis Lagrange in 1793. C. K. Thornhill includes a summary of early gun internal ballistics work in, "A New Special Solution to the Complete Problem of the Internal Ballistics of Guns", and suggests that, since the time of Robins and Lagrange, analyses of the gun problem have generally followed one of three methods. The first method involves a solution to the complete fluid dynamic equations of flow using the theory of finite-amplitude waves in gases. The second method involves a reduction of the problem to the solution of ordinary differential equations. Solutions employing this second method are known as "mixed solutions", and do not involve the complete fluid dynamic equations of flow. Solutions involving the third method are

known as "special solutions". Such solutions do involve the complete fluid dynamic equations of flow, are self-similar in nature, and require that the initial conditions be precisely those which insure self-similarity (Ref 7:1).

The conversion of chemical energy of the propellant to kinetic energy of the shell is a complex process, and an exact analytical description of this process does not exist. Every gun internal ballistics analysis employs a number of simplifying assumptions which reduce the problem to a model which can be more readily analyzed. In order to provide a basis of comparison between the present work and other studies the most commonly-used assumptions found in other gun ballistics studies will now be discussed.

One of the first simplifications applied to the gun problem was that the propellant was completely burned before the shell motion was permitted to begin. This assumption was used by Robins and Lagrange in the eighteenth century, then by Love and Pidduck during the early part of the twentieth century (Ref 3:347), and finally in a more modern work by Seigel (Ref 7). A second assumption includes the presence of burning propellant in the analysis, but requires that the propellant velocity be the same as the gas velocity. The works of Baer and Hitchcock are examples of studies which employ this assumption (Refs 1, 2, and 5). A third assumption is that the chamber may be represented by an "effective chamber" which has the same volume as the actual chamber but a diameter equal to that of the bore. Seigel

states that the "effective chamber" assumption is invalid, however, in that an analysis incorporating this assumption neglects certain significant compression effects which occur as a result of the area change in the chamber (Ref 7:28). A final assumption is that the gas density is only a function of time. The works of Heiney (Ref 4:5) and Hitchcock (Ref 5:4) illustrate that this assumption is a sufficient condition for a linear gas velocity distribution.

Such assumptions as the ones discussed above do serve to reduce the gun problem to a more ammenable form, but in doing so they tend to form models which deviate somewhat from physical reality. One might well question the validity of a model which represents a chambered, propellant-burning gun with a non-chambered, non-propellant burning tube, yet the results of many such simplified analyses agree quite satisfactorily with experimental results (Refs 1, 2, 4, 5, 6 and 7). Recently, however, evidence has appeared which indicates that conventional theory is not always providing acceptable results, particularly for power-burning guns with muzzle velocities in excess of 5000 feet per second (fps). Baer points out that as muzzle velocities increase beyond 5000 fps conventional internal ballistic theory is unable to predict detailed gun performance (Ref 1:535). Further, Hitchcock noted an increased deviation between theory and experiment for muzzle velocities in the 5500 - 6500 fps range (Ref 5:25-26).

The Present Work

The present work has two objectives. The first is to model the gun internal ballistics process in such a manner as to be independent of the four commonly-used assumptions described above. The second objective is to use the results of this model to explain the deviations between theory and experiment for high-speed guns noted by Baer and Hitchcock.

Section II is a two-part section devoted to a discussion of the analytical model used in this work. The first part contains a discussion of the fundamental assumptions used as a basis for the model, while the second part contains a word description of the operation of the model. Section III contains the working equations, the derivation of these equations, and a detailed list of the assumptions used in deriving them. Section IV contains a discussion of the results. The conclusion reached as a result of this work and some recommendations for future work are contained in Section V.

A Fortran Extended computer program was created to perform the numerous storing, searching, and computational routines involved in the solution. Pertinent information about the type of computer used, storage requirements, program run time, as well as a simplified logic diagram, a program listing, and a sample output are contained in the appendices. A brief glossary of terms peculiar to the gun internal ballistics field is provided in Appendix E.

II. The Analytical Model

Fundamental Assumptions

The analytical model is based upon two fundamental assumptions. The first is that for small but finite increments of time the actual internal ballistics process may be represented by an artificial sequence of four separate "phases". This sequence consists of a constant volume energy transfer phase, a shell motion and wave propagation phase, a propellant motion phase, and a gas expansion and mass transfer phase. The implication of the assumption is that for small but finite increments of time the net result of this artificial sequence of phases is approximately the same as if all the phases had occurred simultaneously. This sequence bears a general resemblance to a thermodynamic cycle in that a system is changed from an initial set of conditions to a final set of conditions by an orderly progression of events; for this reason an individual sequence will hereafter be referred to as a "cycle".

The second fundamental assumption is that the column of gas and propellant between the breech and the shell may be represented by a fixed number of individual gas "subvolumes". At any instant of time the gas properties within an individual subvolume are considered to be constant. These property values may, however, vary from one subvolume to another. Gas and propellant mass transfer may occur between subvolumes, but only at separate and specified times during the cycle.

The purpose of these two assumptions is to simplify the internal ballistics process into one that is more readily analyzed. The first assumption separates the complex internal ballistics process into more fundamental processes: constant volume combustion, one-dimensional motion and mass transfer, and finite-amplitude wave propagation. The second assumption simplifies the analysis of the gas and propellant column by separating it into a number of small constant-property-value subvolumes. These subvolumes are then analyzed using the theory of finite-amplitude waves in gases, a basic energy equation, and simple equations of mass motion and mass transfer.

Word Description of the Model

Overall Physical Description. The diameter change from the chamber to the bore normally occurs over a finite length of the gun barrel. For this analysis this area change is considered to occur at a single location. No other changes in the physical description of the gun barrel are made. In this work the region between the breech and the area-change location will be referred to as the "chamber", while the remainder of the gun barrel will be referred to as the "bore".

The projectile is initially positioned at the location of the area change and the chamber is divided into a fixed number of cylindrical segments. The axis of rotation of each segment is the same as the axis of rotation of the chamber. All segments initially contain the same quantity

of gas mass, the same number of propellant grains, and have the same volume. Further, all segments initially have identical gas property values.

The Gas Subvolumes. The gas which occupies the available space between the boundaries of a single segment forms the gas subvolume. Gas subvolume properties change as a result of expansion (wave propagation) and mass change. Gas mass change occurs as a result of mass transfer across the gas boundaries and as a result of a propellant burn.

The Propellant Segments. The amount of mass released by a given mass of burning propellant during a finite increment of time is dependent upon the surface area of the propellant, the relative flow of gas past the propellant, and the pressure of the gas surrounding the propellant. In order to account for the surface area of the propellant as it burns, the number of propellant grains in each propellant segment is fixed at the initial value. Also, all grains within a single propellant segment are considered to burn at the same rate. Hence all the grains within a single propellant segment are kept identical with one another, and the mass released by a single propellant segment during a single burn time increment is simply the mass released by a single grain times the number of grains in the segment. Since the number of grains in a single segment is fixed, it can be seen that the mass of propellant in a single segment can only decrease. Location of the various propellant segments is

accomplished by fixing the length of each segment at the original value.

There is no requirement that a propellant segment be located entirely within a gas subvolume; therefore if a single propellant segment happens to be located such that its length is divided by a gas boundary the burning rate of that segment should actually be influenced by the two different velocities and pressures of the two subvolumes. When this situation occurs the burning rate of the entire propellant segment is determined by the average pressure and relative velocity of the two subvolumes.

The Gas Boundaries. The gas boundaries have three functions. The first is to serve as solid, fixed boundaries during the constant-volume energy transfer phase of the cycle. The second function is to act as planes of mass transfer during the gas expansion and propellant-motion phases of the cycle. The third function is to serve as locations for the finite-amplitude waves which are used to change the gas property values following an incremental shell motion. If a wave travelling toward the breech is designated an "upstream" (against the gas flow) wave and a wave travelling toward the shell is designated a "downstream" wave, then it can be seen that there will be four possible types of waves: an upstream expansion wave, an upstream compression wave, a downstream expansion wave, and a downstream compression wave. Gas properties are changed whenever one of these waves travels across a gas subvolume. Since the gas

properties within each subvolume are required to be constant at any instant of time, a wave is not permitted to be located between two gas boundaries. A wave is propagated to the next boundary only if it is determined that there is sufficient time remaining in the time increment for this motion to occur. If the wave cannot cross at least half-way across the subvolume it is fixed at its current location.

Gas Subvolume Containing the Area Change. The gas subvolume which contains the area change from the chamber to the bore is an exception to the normal constant-diameter gas subvolumes, and is therefore treated somewhat differently. A "property discontinuity" is considered to exist at the location of the area change, and the gas property values on the chamber side of the subvolume are not necessarily the same as the gas property values on the bore side. Further, unlike other subvolumes, internal gas mass transfer does occur from the chamber side to the bore side. This process is described in the Word Description of the Model Operation section below.

Word Description of the Model Operation. In order to illustrate the operation of the model as well as clarify the functions of the previously-described features a brief description of a typical cycle will now be given.

The first phase of the cycle is the constant-volume energy transfer phase. All motion is frozen, then each propellant segment is burned for a single time increment. This burning process changes the pressure, density,

temperature, and gas volume in each subvolume. The mass of each propellant segment is, of course, reduced. After this increment of burning is completed and the appropriate adjustments have been made in the subvolume property values the cycle proceeds to the second phase.

The second phase is the projectile motion and wave propagation phase. The average of the pressure before the burn and the pressure after the burn in the subvolume adjacent to the projectile is considered to act upon the shell for one time increment. This force changes the projectile acceleration and velocity and moves the shell to a new location. The change in projectile velocity is considered to be impulsive and to generate a finite expansion wave which, later in the cycle, will propagate toward the breech. The model first propagates expansion waves from earlier projectile motion, then procedes to other types of waves which may be present, including the recently-generated expansion wave from the current projectile motion. If a compression wave "catches up" with another wave of like kind and direction the wave strengths are combined prior to further propagation. Different types of waves or like waves travelling in opposite directions are not combined. Waves which encounter the projectile or breech are reflected in like kind, and a wave which crosses the gas subvolume containing the area change is reflected as two waves of appropriate strength and direction (Ref 7:28). When all present waves have been propagated as

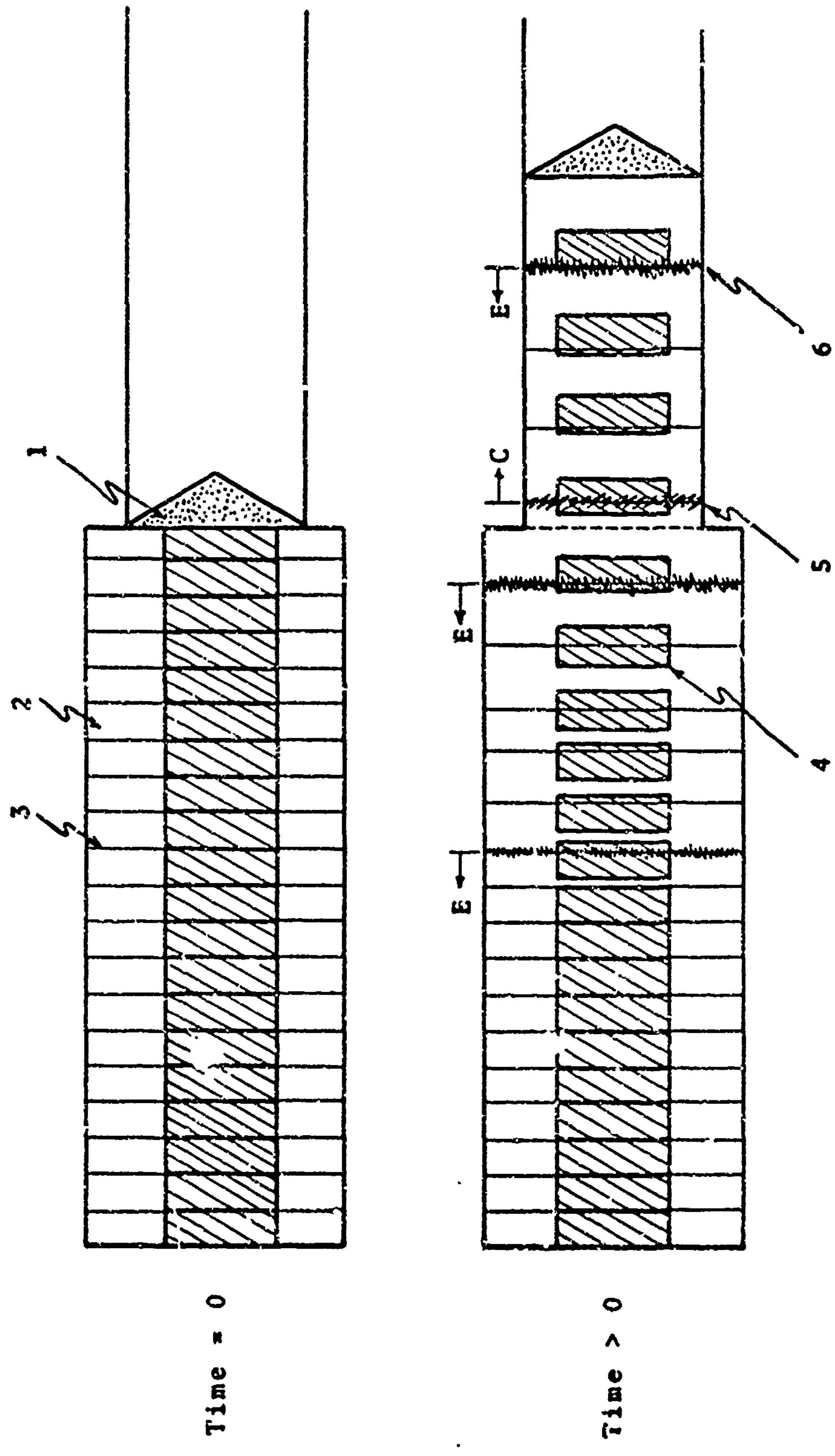
far as possible during a single time increment the cycle proceeds to the third phase.

The third phase of tho cycle is the propellant motion phase. The pressure drop across the length of the segment is determined, then an estimated drag coefficient and an estimated effective area are used in a simplified equation of motion to determine the new velocity and position of the propellant segment. When all the segments have been moved the cycle proceeds to the fourth and final phase.

The last phase of the cycle is the gas expansion and mass transfer phase. The net effect of each wave that has crossed a single gas boundary is used to determine the new velocity of that boundary. Once the new velocity is determined the boundary is moved at that velocity for a single time increment. The boundary velocity, barrel cross-sectional area, and the gas density of the next downstream subvolume are used to determine the gas mass transfer across the boundary during this motion. After all boundaries have been relocated the total propellant mass within each subvolume is redetermined. With the subvolume pressure held at the value determined during the wave propagation phase, the remainder of the gas property values are then determined from an equation of state. This final property determination marks the end of the cycle.

The cycle just described is repeated until it is determined that the projectile position exceeds the length of the barrel, at which time the analysis ends. Provisions are made

in the model to check for propellant burn-out prior to projectile exit in order that the propellant-burning and motion parts of the cycle may be deleted. Figure 1 illustrates the physical appearance of the model prior to projectile motion and at some later time.



1: Shell
2: Gas Subvolume
3: Gas Boundary
4: Propellant Segment
5: Compression Wave
6: Expansion Wave

Fig. 1. Physical Setup of Model.

III. Analysis

Analytical Assumptions

The two fundamental assumptions which form the basis for the analytical model have been previously discussed in the first part of Section II. The following analytical assumptions have also been used:

(a) All motion is one-dimensional.

(b) Propellant burning takes place under constant-volume conditions.

(c) The propellant burning rate is a function of gas pressure and relative gas-to-propellant velocity.

(d) The propellant grains burn uniformly over their entire surface.

(e) The gas obeys the Nobel-Abel equation of state with a constant covolume.

(f) The gas has a constant ratio of specific heats.

(g) The gas subvolume boundaries are adiabatic.

(h) The drag coefficient for the propellant segments is constant.

(i) The drag on the projectile consists of a variable aerodynamic drag and a constant friction drag.

(j) The diameter change from the chamber to the bore occurs at a single location.

(k) A normal shock forms ahead of the projectile as soon as the projectile motion begins.

(1) The presence of the propellant exerts no influence on the wave propagation process.

The following are considered to be negligible:

(a) Heat transfer to the gun walls and to the projectile.

(b) Friction losses between the gas and the gun walls.

(c) Friction losses between the propellant and the gun walls.

(d) Drag due to projectile rotation (rifling drag).

(e) Losses due to propellant gas leaking past the projectile.

(f) The pressure gradient between the front of the projectile and the downstream side of the normal shock.

(g) Effects due to gun recoil.

(h) Effects due to variations in the initial temperature of the propellant.

The Working Equations

The Energy Equation. The first law of thermodynamics for a constant volume subvolume with no mass flow is

$$Q = \Delta U \qquad (1)$$

where, for the constant volume adiabatic combustion used in this work

$$q = \frac{F}{\gamma_g - 1} \quad \text{(Ref 3:175)} \qquad (2)$$

and

$$\Delta u = C_v \Delta T \tag{3}$$

where γ_g = propellant gas ratio of specific heats

For the gun problem

$$C_v \equiv \frac{R_g}{\gamma_g - 1} \quad \text{(Ref 8:126)} \tag{4}$$

Since F, the "force constant" is defined as

$$F \equiv R_g T_{iso} \tag{5}$$

Eq (1) becomes

$$\frac{R_g T_{iso}}{\gamma_g - 1} = \frac{R_g (\Delta T)}{\gamma_g - 1} \tag{6}$$

For a finite quantity of Eqs (2) and (3) may be expressed

$$Q = \frac{R_g T_{iso}}{\gamma_g - 1} \quad \Delta M_g$$

$$\Delta U = \frac{R_g}{\gamma_g - 1} \quad (M_f T_f - M_i T_i) \tag{8}$$

where M_f = final mass of gas

M_i = initial mass of gas

T_f = final gas temperature

T_i = initial gas temperature

Equating (7) and (8)

$$\frac{R_g T_{iso}}{\gamma_g - 1} \quad (M_f - M_i) = \frac{R_g}{\gamma_g - 1} \quad (M_f T_f - M_i T_i) \tag{9}$$

$$T_f = T_{iso} \left(1 - \frac{M_i}{M_f} \right) + T_i \frac{M_i}{M_f} \tag{10}$$

Equation of State. The equation of state used is the "Nobel-Abel" equation of state with a constant covolume

$$P(V - Mb) = MR_g T \tag{11}$$

where b = covolume

Mass Change Due to Propellant Burn. The change in mass for a single propellant segment during a single time increment is

$$\Delta M_g = -\Delta M_p = -(\Delta V_p)(\rho_p)(N_p) \tag{12}$$

where ΔV_p = change in a single grain volume

ρ_p = propellant density

N_p = number of grains per segment

M_p = propellant mass

M_g = gas mass

The propellant burn rate is taken to be

$$\dot{R} = \beta(P/1000)^{n} + K_c v_r \quad \text{(Ref 5:9)} \tag{13}$$

where $\dot{R}$ = propellant burn rate (length/time)

β = burn rate at 1000 psia and v_r = 0

P = gas pressure

n = burn rate exponent

K_c = erosive burn constant

v_r = relative gas-to-propellant velocity

The volume change of a single grain is

$$\Delta V_g = |(A_p R_p) - (A_p R_p)'| \qquad (14)$$

where A_p = grain surface area

R_p = grain radius

$(\ )'$ = value after propellant burn

The absolute value in Eq (14) is necessary because some grains are designed such that the surface area increases during the initial burn process. The surface area vs. grain radius for the particular problem studied was obtained from tabular data (Ref 5:38-41). Equations (12), (13), and (14) are used to determine M_i vs. M_r in Eq (10).

Wave Propagation. The pressure change induced by a finite-amplitude wave of strength ΔV is given by

$$\Delta P = -\rho a(\Delta v) \quad \text{(Ref 7:10-12)} \qquad (15)$$

where ΔP = finite pressure change

ρ = gas density ahead of wave

a = sonic velocity ahead of wave

Δv = finite velocity change

Wave velocity is given by

$$V_w = a \pm v_g \quad \text{(Ref 7:11)} \qquad (16)$$

where v_w = wave velocity

v_g = gas velocity

a = gas sonic velocity

As mentioned previously in Section II, a wave which encounters the gas subvolume containing the chamber-bore area change is split into two waves. For example, a bore-side upstream-travelling expansion wave is split into a compression wave which travels back toward the shell and an expansion wave which continues on toward the breech. The strengths and directions of the split waves are determined in the following manner.

Consider an upstream-travelling rarefaction (expansion) wave Δv_1 which has just reached the bore side of the gas subvolume containing the chamber-bore area change (Fig. 2a). The change in pressure on the bore side of the subvolume is determined with Eq (15)

$$\Delta P_1 = -\rho_b a_b \Delta v_1$$

where ρ_b = bore-side density

a_b = bore-side sonic velocity

The wave is advanced to the point of area change and the new bore-side pressure and velocity values are determined (Fig. 2b)

$$P_{b_1} = P_b + \Delta P_1 \tag{17}$$

$$v_{b_1} = v_b + \Delta v_1 \tag{18}$$

The decreased pressure on the bore side induces as increased mass flow from the chamber side. The amount of mass

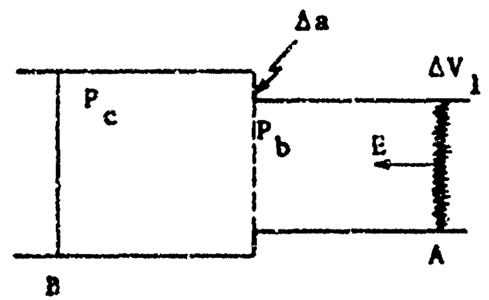


Fig. 2a: Expansion Wave Approaching Δa

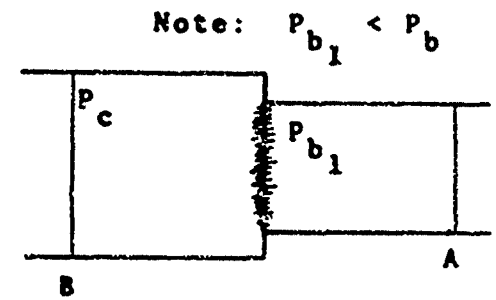


Fig. 2b: Wave at Δa

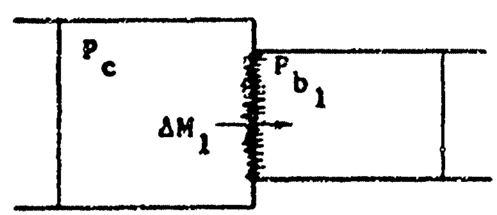


Fig. 2c: Internal Mass Transfer

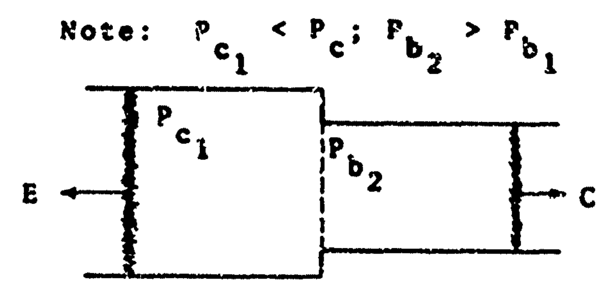


Fig. 2d: Resultant Wave Split

Fig. 2. Chamber Subvolume "Wave Split".

transferred from the chamber side to the bore side is

$$\Delta M_1 = \rho_{ch} A_b v_{b_1} (\Delta t) \tag{19}$$

where ρ_{ch} = chamber side density

A_b = bore side area

Δt = time increment

The amount of gas mass on the bore side is therefore increased by an amount ΔM_1 while the gas mass on the chamber side is decreased by the same amount (Fig. 2c). If temperature is assumed to be constant during this process the new bore-side pressure becomes

$$P_{b_2} = \frac{(M_b + \Delta M_1) R_g T_b}{[V_b - b(M_b + \Delta M_1)]} \tag{20}$$

while the new chamber-side pressure is

$$P_{c_1} = \frac{(M_b - \Delta M_1) R_g T_c}{[V_c - b(M_c - \Delta M_1)]} \tag{21}$$

where T_b = bore-side temperature

T_c = chamber-side temperature

It can be seen from Eqs (20) and (21) that P_{b_2} will be greater than P_{b_1} (but still less than P_b) while P_{c_1} will be less than P_c. Hence the net effect is to produce a downstream-travelling compression wave of strength $\Delta P_2 = P_{b_2} - P_{b_1}$ (positive) at Δa (Fig. 2a) and an upstream-travelling expansion wave of strength $\Delta P_3 = P_{c_1} - P_c$ (negative) at B in

in Fig. 1d. A similar analysis holds for the other types of waves.

Propellant Segment Motion. Propellant segment motion is determined from a simplified equation of motion. It is assumed that the sum of the forces Σf_p acting on a single propellant segment for a single time increment is

$$\Sigma f_p = (\Delta P)A_e + D_p \tag{22}$$

where ΔP = pressure difference across the segment length

A_e = estimated "effective area"

D_p = estimated aerodynamic drag

The estimated effective area of the segment is taken to be

$$A_e = \frac{V_p}{L_p} \tag{23}$$

where V_p = volume of the propellant segment

L_p = fixed length of the propellant segment

The estimated aerodynamic drag on the propellant segment is taken to be

$$D_p = 1/2\ \rho_g v_r^2 A_e C_d \tag{24}$$

where ρ_g = gas density

v_r = relative velocity of gas past the propellant

C_d = estimated drag coefficient (constant)

If the acceleration of the segment a_p is approximated by

$$a_p = \frac{\Delta v_p}{\Delta t} \tag{25}$$

then Newton's second law applied to the propellant segment is

$$-(\Delta P)A_e + 1/2\ \rho_g v_r^2 A_e C_d = m_p \frac{\Delta v_p}{\Delta t} \tag{26}$$

where m_p = propellant segment mass

v_p = propellant segment velocity

v_r = relative velocity of gas past propellant (assumed to be positive at all times)

If Δv_p is taken to be

$$\Delta v_p = v_p' - v_p \tag{27}$$

where v_p' = the velocity at the end of Δt

v_p = the velocity at the beginning of Δt

then Eq (26) may be solved for v_p'

$$v_p' = v_p + \frac{\Delta t}{m_p}\left[(\Delta P)A_e + 1/2\ \rho_g v_r^2 A_e C_d\right] \tag{28}$$

<u>Aerodynamic</u> <u>Drag</u>. The aerodynamic drag pressure P_d exerted on the projectile on the muzzle side of the projectile is given by

$$P_d = P_a\left\{1 + \frac{\gamma_a v_{pr}}{2a}\left[\left(\frac{\gamma_a + 1}{2}\right)\frac{v_{pr}}{a} + \sqrt{\left[\left(\frac{\gamma_a + 1}{2}\right)\frac{v_{pr}}{a}\right]^2 + 4}\right]\right\} \quad \text{(Ref 5:44)} \tag{29}$$

where P_d = aerodynamic drag pressure

P_a = ambient (upstream of shock) pressure

γ_a = ambient ratio of specific heats

v_{pr} = projectile velocity

a = ambient sonic velocity

<u>Projectile Equation of Motion</u>. The equation of motion for the projectile is taken to be

$$(P_{pr} - P_f - P_{ad})A_b = (M_{pr})(a_{pr}) \tag{30}$$

where P_{pr} = pressure on the breech side of the projectile

P_f = estimated constant friction pressure

P_{ad} = aerodynamic drag pressure

M_{pr} = projectile mass

a_{pr} = projectile acceleration

IV. Discussion of Results

Of the two objectives stated in the introduction to this work only the first has been met, and that with extremely limited results. The model has performed acceptably for only one complete cycle following the initial motion of the shell. Results obtained from the second cycle indicate that the model is failing to combine gas and propellant motion in such a manner as to obtain a realistic pressure distribution. Specifically, an unrealistically low pressure in the gas subvolume adjacent to the shell is established early during the second cycle. This low pressure in turn sets up wave reflections from the chamber subvolume with unrealistically high velocity strength values. These erroneous waves are then propagated for the remainder of the time increment, and the resulting model bears little resemblance to the actual physical situation. The excessively low pressure is a direct result of the separation of gas motion from propellant motion. The sudden expansion of the subvolume adjacent to the shell caused by the shell motion increases the volume available to the gas in that subvolume. Because there is no motion of propellant into that subvolume at that point in the cycle, the space that should be occupied by some portion of propellant mass is not; hence the gas expands to fill an unrealistically large volume and the pressure drops.

V. Conclusion and Recommendations

Conclusion

The conclusion reached as a result of the work to date is:

The basic model concept shows promise, but at present the model is failing to realistically represent the combined flow of gas and propellant.

Recommendations

The following recommendations are made concerning this analysis:

1. The basic model concept should be revised to realistically represent the combined flow of gas and propellant in order to preserve a realistic pressure gradient.

2. The propellant segment drag coefficient should be computed from Reynold's number considerations instead of the present constant value.

3. A more accurate representation of the shell sliding friction should be attempted.

4. An allowance for energy loss due to heat transfer should be introduced.

5. Propellant burning rate values should be obtained from tabular data rather than the conventional pressure and erosive burn scheme used in this work.

Bibliography

1. Baer, P. G. "Prediction of High Velocity Solid Propellant Gun Performance by Gas Dynamic Computer Program." Ballistic Research Laboratories Report, Aberdeen Proving Ground, Maryland. 1970.

2. Baer, P. G. "A Mass Point Computer Program for the Gas Dynamic Problems of High Velocity Interior Ballistics." Unpublished report by the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. Undated.

3. Corner, J. Theory of the Interior Ballistics of Guns. New York: John Wiley and Sons, Inc. 1950.

4. Heiney, D. K. "Simplified Interior Ballistics of Closed Breech Guns." AFATL-TR-67-42. Air Force Armament Laboratory Report, Eglin Air Force Base, Florida. April 1967.

5. Hitchcock, J. E. "Gun Interior Ballistics." AFRPL-TR-69-211. Air Force Rocket Propulsion Laboratory Report, Edwards Air Force Base, California. September 1969.

6. Seigel, A. E. "The Theory of High Speed Guns." NATO Agardograph 91. North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, United States Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland. May 1965.

7. Thornhill, C. K. "A New Special Solution to the Complete Problem of the Internal Ballistics of Guns." RARDE Report 2167. Royal Armament Research and Development Establishment, Fort Halstead, Kent, England. February 1967.

Appendix A

Computer Program Features and Requirements

Computer Program Features

Debug Mode of Operation. A self-debugging feature is built into the program to enable automatic debugging during future program modifications. The self-debugging feature is activated by replacing the "FTN." control card at the beginning of the deck with an "FTN(D)" control card, and increasing the memory requirement by 12K. The debug feature causes the following to occur automatically:

a. Automatic bounds check on all arrays.

b. Printout of certain key program variables values whenever these value. change, along with the program location of the change.

Logic tracing is available by adding a

```
     C$    TRACE
col: 12    7
```

card immediately after the "C$ DEBUG" card in the deck. Further information on the debug mode of operation is contained in Chapter 11 of the Control Data 6400/6500/6600 Computer Systems Fortran Extended Reference Manual.

Solution of the Preburned Propellant Problem. The preburned propellant problem may be considered with this program by:

a. Entering all propellant data as if the propellant were going to be burned.

b. Setting the value of the variable "NOCH" to "2" on the appropriate data card.

Computer Program Requirements.

Language:	Fortran Extended.
Computer:	Control Data 6600 (Digital).
Storage	36K (Binary) 45K (Compile/no debug) 60K (Debug)
Run time:	Undetermined.

Appendix B

Computer Program Symbols

Computer Program Symbols

NOTE: The term "bore-side" refers to the bore side of the subvolume containing the chamber-bore area change. "Chamber-side" refers to the chamber side of the same subvolume.

Symbol	Definition
A	Area
ADP	Aerodynamic drag pressure
AGRO	Average gas density
AGV	Average gas velocity
A1	Multipurpose variable
BA	Bore area
BD	Bore diameter (input)
BETA	Pressure burn coefficient (input)
BGMAS	Bore-side gas mass
BP	Bore-side pressure
BRO	Bore-side gas density
BT	Bore-side temperature
BURNA	Propellant burn area (tabular input)
BV	Bore-side gas velocity
BXP	Pressure burn exponent (input)
CA	Chamber area
CD	Propellant drag coefficient (input)
CGMAS	Chamber-side gas mass
CHD	Chamber diameter (input)
CHL	Chamber length (input)
CHRO	Chamber-side gas density

Symbol	Definition
CHV	Chamber-side gas velocity
CL	Fixed length of propellant segments
CMAS	Propellant segment mass
CMASS	Total propellant mass in subvolume (output only)
CMIG	Igniter charge mass (input)
COVOL	Covolume (input)
CP	Chamber-side pressure
CRO	Propellant density (input)
CT	Chamber-side temperature
CV	Propellant segment velocity
CX	Propellant segment position
DCM	Mass Change due to burn
DIST	Distance (various uses)
DM	Incremental mass change (various uses)
DMC	Center section of DCM for KTYP = 10 and KTYP = 11 (Ref to Fig. 3).
DML	Left side of DCM (Refer to Fig. 3).
DMR	Right side of DCM (Refer to Fig. 3).
DP	Pressure change
DT	Time increment
DV	Velocity change
DVB	Bore-side velocity change
DVC	Chamber-side velocity change
DVSUM	Sum of velocity changes at an individual gas boundary
EBK	Erosive burn constant (input)
F	Gun constant (also known as "force constant") (input)

Symbol	Definition
FP	Friction pressure (input)
GAMA	Ambient ratio of specific heats (input)
GAMG	Propellant gas ratio of specific heats (input)
GMAS	Subvolume gas mass
GNMAS	Initial propellant grain mass (input)
GNS	Number of grains per propellant segment
GRAD	Grain burn radius (tabular input)
GUNL	Gun barrel length (input)
I	Counter (various uses)
IB	Bore gas boundary reference
ID	Program section identifier
IS	Stored gas boundary value
IWA	"Is wave available for propagation" indicator IWA = 0 Wave present and ready for propagation IWA = 1 No wave present IWA = 2 Wave present but already propagated during this time increment
IX	Index (used during wave propagation) Wave type: J = 1 Upstream expansion J = 2 Downstream expansion J = 3 Upstream compression J = 4 Downstream compression
JB	Bore-side wave type
JC	Chamber-side wave type
JS	Stored wave type value
K	Counter (various uses)

Symbol	Definition		
KCHW	Index:	KCHW = 0	Wave is not chamber reflection
		KCHW = 1	Wave is chamber reflection from area change subvolume
		KCHW = 2	Wave is bore reflection from area change subvolume
KTYP	Type of propellant segment (Refer to Fig. 3)		
L	Counter (various uses)		
LTYP	Index:	LTYP = 0	Propellant segment within subvolume
		LTYP = 1	Propellant segment divided by upstream gas boundary
M	Counter (various uses)		
N	Propellant segment counter		
NB	Number of gas boundaries (input)		
NOCH	Index:	NOCH = 0	Propellant segment present (input) in subvolume
		NOCH = 1	Propellant segment not present in subvolume
		NOCH = 2	No propellant in gun
NTAB	Number of tabular entries in the grain surface area (input) vs burn distance table		
OBP	Bore-side pressure before incremental burn		
OCP	Chamber-side pressure before incremental burn		
OP	Normal subvolume pressure before incremental burn		
ORAD	Grain burn radius before incremental burn		
OSHV	Shell velocity at beginning of time increment		
OSURFA	Grain surface area before incremental burn		
P	Subvolume gas pressure		
PA	Ambient pressure (input)		

Symbol	Definition
PDIF	Pressure difference across a single propellant segment length
POS	Position (used in output)
PRES	Pressure (various uses)
PSHOT	Shell start pressure (also known as shot start pressure) (input)
PSTOR	Stored pressure value
R	Current grain burn radius
RDOT	Grain burn rate
RG	Propellant gas constant
RO	Subvolume gas density
ROA	Ambient gas density (input)
ROW	Density (used in output)
SHA	Shell acceleration
SHM	Shell mass (input)
SHV	Shell velocity
SHX	Shell position
SURFA	Grain surface area after incremental burn
SV	Gas subvolume sonic velocity
SVA	Ambient sonic velocity
SVK	Computational constant
T	Subvolume gas temperature
TA	Ambient temperature (input)
TAC	Time available to chamber-bore area change reflections
TAV	Time available (various uses)
TCMAS	Total propellant mass in subvolume

Symbol	Definition
TCMASB	Total bore-side propellant mass
TCMASC	Total chamber-side propellant mass
TEMP	Temperature (used in output)
TIME	Time expired
TISO	Isochoric flame temperature (input)
TOTCM	Total propellant mass (input)
TTC	Time to cross subvolume (used in wave propagation)
TYPGUN	Type of gun being analyzed (input)
TYPROP	Type of propellant (input)
V	Subvolume gas velocity
VEL	Velocity (used in output)
VOL	Volume (various uses)
W	Stored value of wave strength
WDIST	Distance (various uses)
WV	Wave velocity
X	Gas boundary position
XMR	Propellant mass ratio (before burn vs after burn)
XNB	Same as NB
XRAD	Grain burn radius

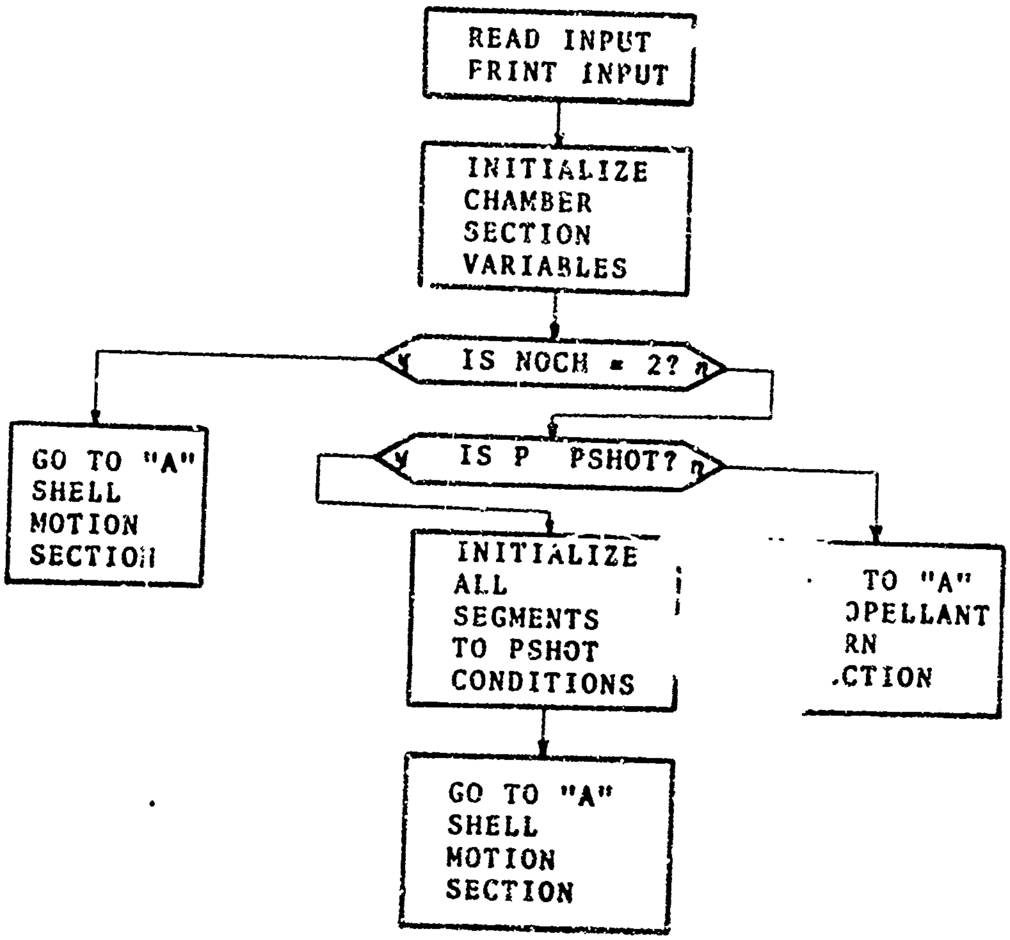
Appendix C

Simplified Computer Program

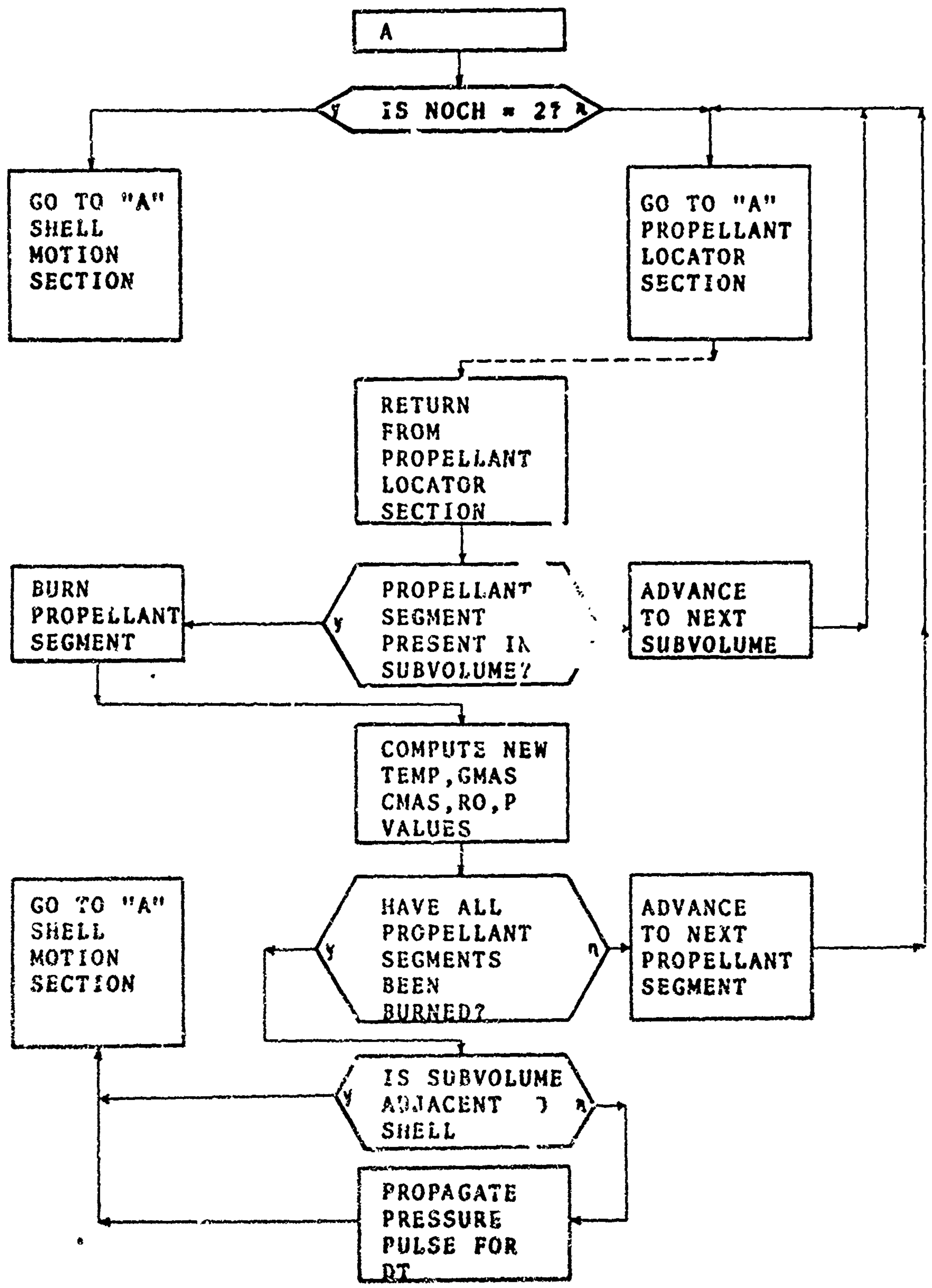
Logic Diagram

Simplified Computer Program Logic Diagram

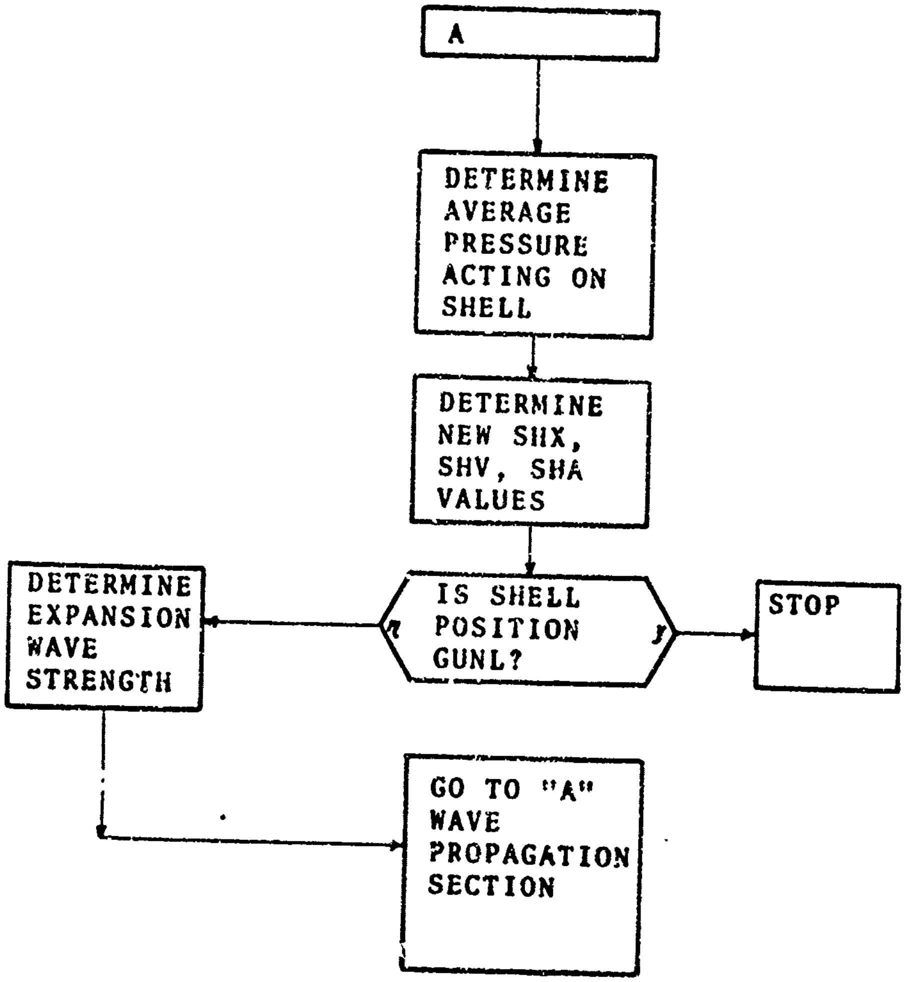
INITIALIZATION SECTION



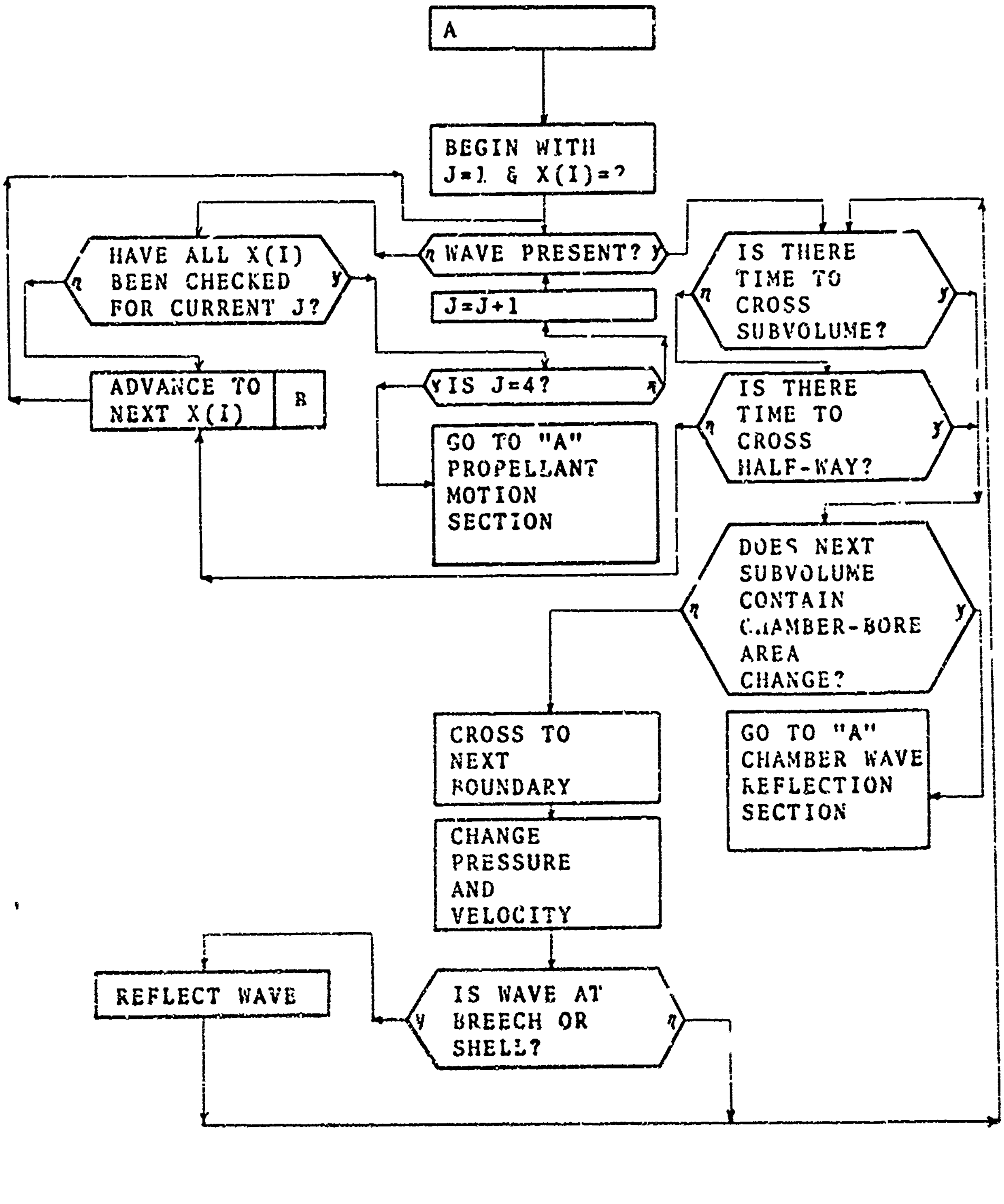
PROPELLANT BURN SECTION



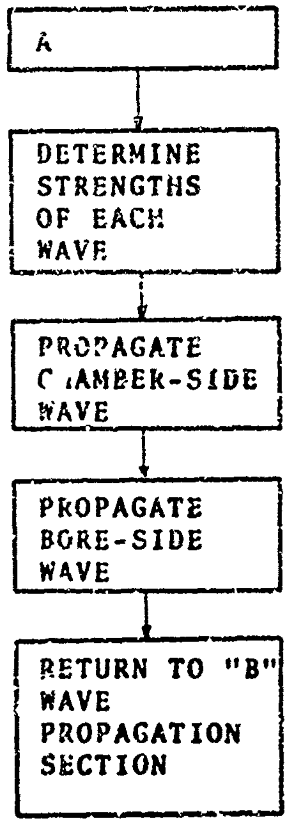
SHELL MOTION SECTION



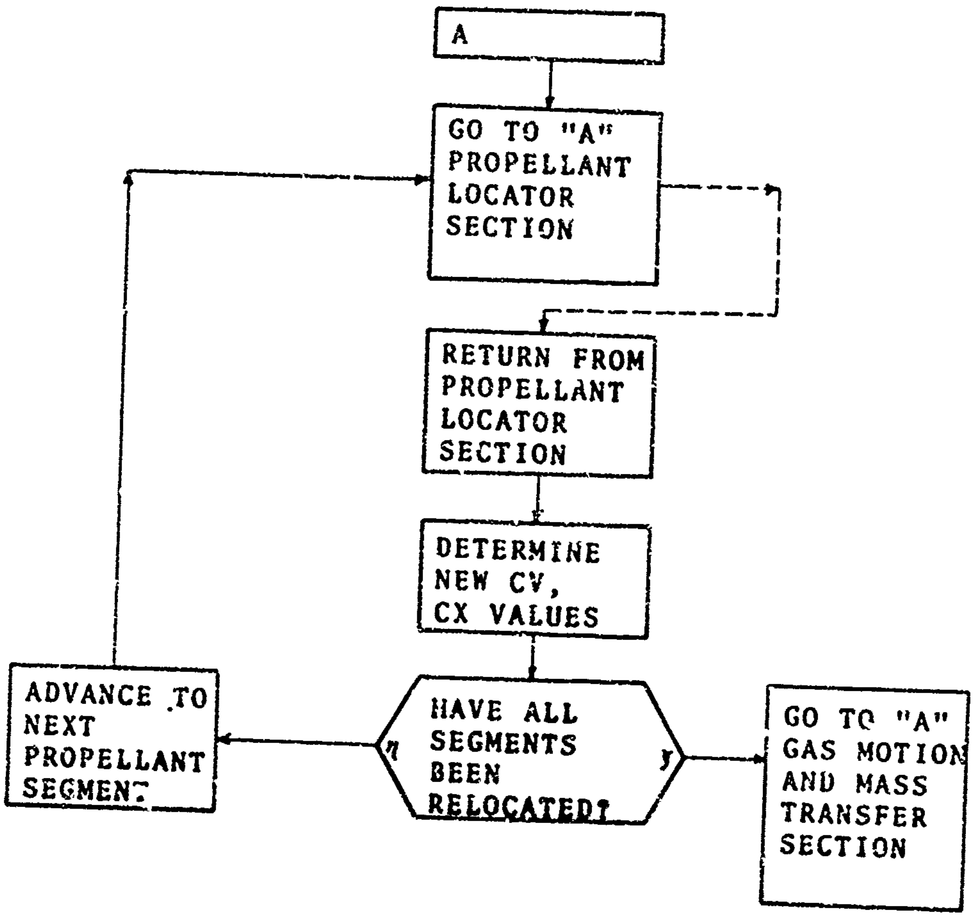
WAVE PROPAGATION SECTION



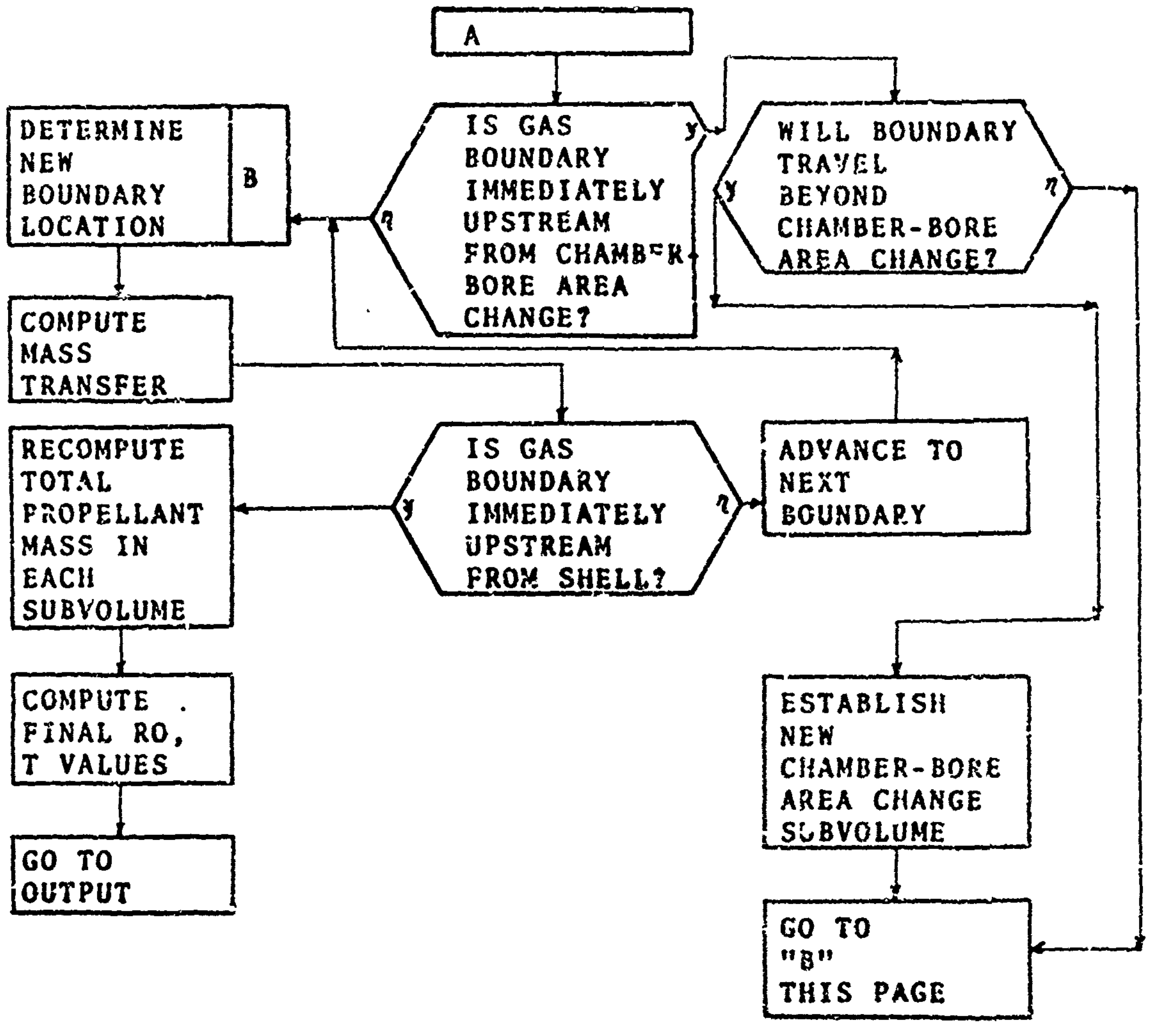
CHAMBER WAVE REFLECTION SECTION



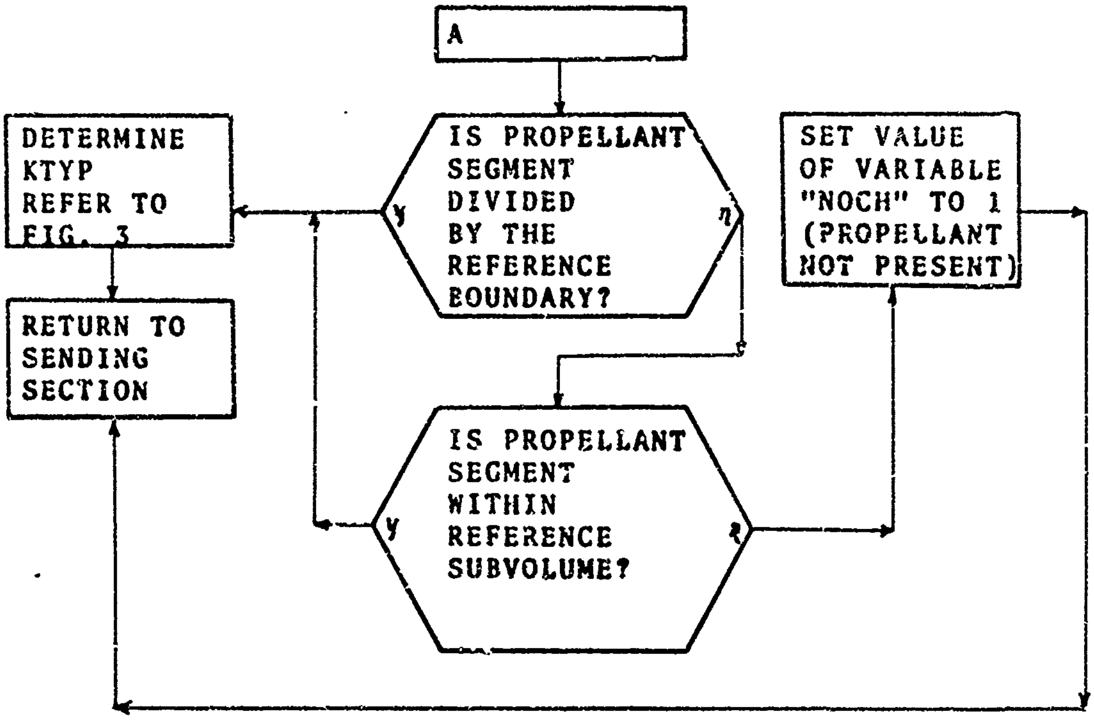
PROPELLANT MOTION SECTION



GAS MOTION AND MASS TRANSFER SECTION



PROPELLANT SEGMENT LOCATOR SECTION



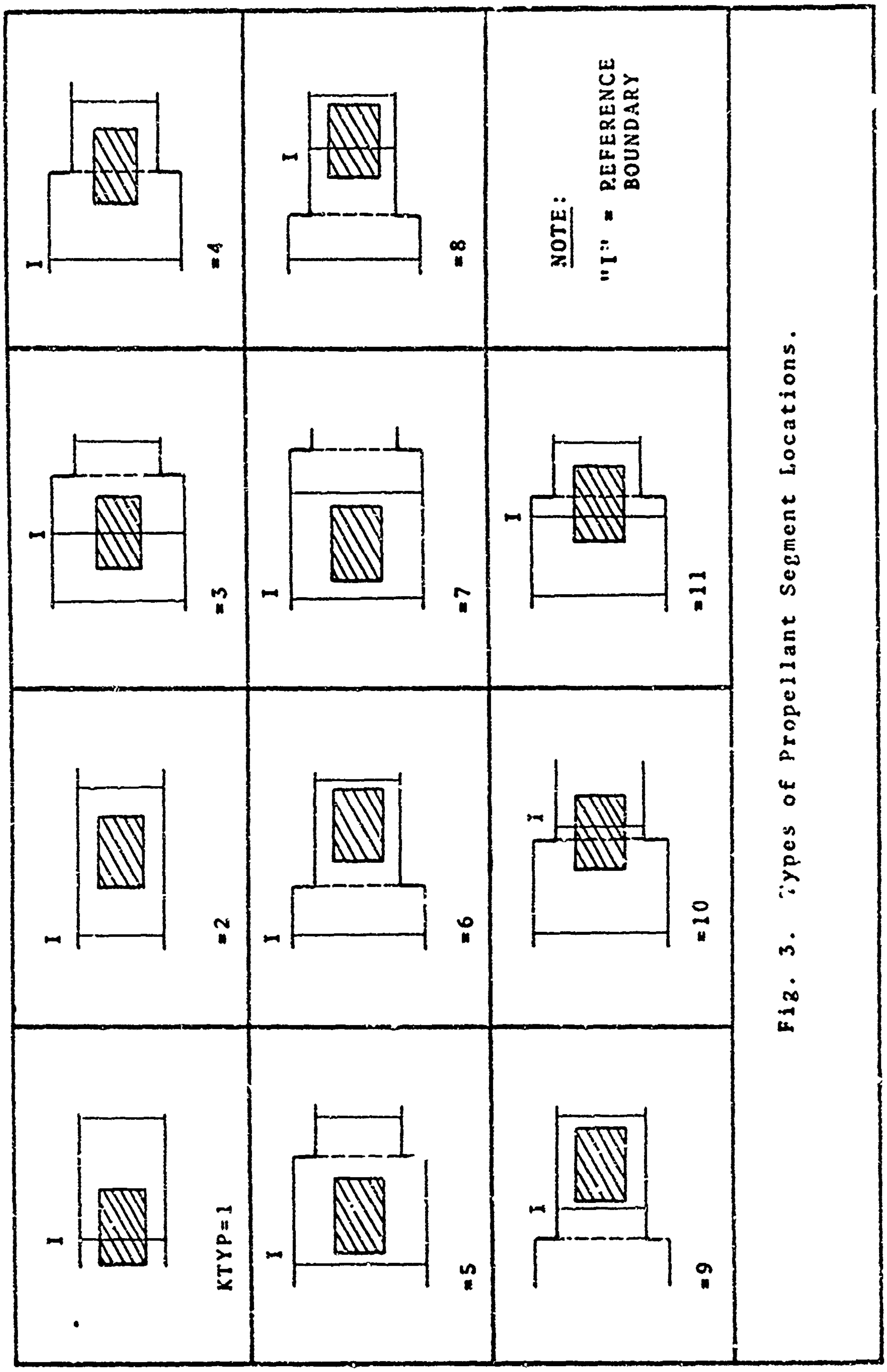


Fig. 3. Types of Propellant Segment Locations.

Appendix D

Computer Program Listing

and

Sample Output

```
  GUN                                             CDC 6600 FTN V3.0-279C OPT=1  02/07/72   1

        PROGRAM GUN(INPUT,OUTPUT,DEBUG=OUTPUT)
 C      DEBUG
 C$     ARRAYS
 C$     STORES(BGVOL,BP,BT,BV,CGVOL,CHV,CP,CT,CV,DIST,DF,DV,I,IB,ID,IJ)
 C$     STORES(IWA,IX,J,JB,JC,JS,K,KCHW,L,M,N,NOCH,P,PDIF,SHA,SHV,SHX)
 C$     STORES(CMAK,BMAK,CVC,DVB,DMK,ARATP,ARATT)
 C$     STORES(T,TAV,TCMAS,TCMASB,TCMASC,TTC,V,VOL,W,X,CX)
 C$     STORES(LTYP,KTYP,WDIST,DVSUM,GMAS,BGMAS,CGMAS,RO,CHRO,BRO,DM,DMC)
 C$     STORES(DMR,CMAS)
*****************************************************************************
*                                                                           *
*       GUN INTERNAL BALLISTICS PROBLEM                                     *
*                                                                           *
*****************************************************************************
        DIMENSION P(50),V(50),RO(50),T(50),GMAS(50),TCMAS(50),DVSUM(50)
        DIMENSION CV(50),CMAS(50),R(50),CX(50)
        DIMENSION X(51),IWA(51,4),W(51,4),BURNA(20),GRAD(20)
*****************************************************************************
*                                                                           *
*       READ INPUT VALUES                                                   *
*                                                                           *
*****************************************************************************
        READ 2000,TYPGUN,TYPROP
        READ 2001,GUNL,CHL,CHD,PD
        READ 2001,SHM,TOTCM,CMIG
        READ 2001,PSHOT,FP
        READ 2001,F,TISO,GAMG,COVOL
        READ 2001,CRO,GNMAS,CP
        READ 2001,BETA,BXP,ERK
        READ 2001,PA,TA,ROA,GAMA
        READ 2002,NTAB,NB
        READ 2003,(GRAD(I),BURNA(I),I=1,NTAB)
        READ 2002,NOCH
        PSHOT=4000.
        DT=.00005
        SVA=SQRT(1.4*32.174*53.35*TA)
        DT=.00001
*****************************************************************************
*                                                                           *
*       PRINT INPUT VALUES                                                  *
*                                                                           *
*****************************************************************************
        PRINT 3000
        PRINT 3010,TYPGUN
        PRINT 3020,GUNL
        PRINT 3030,CHL
        PRINT 3040,CHD
        PRINT 3050,PD
        PRINT 3060
        PRINT 3070,PSHOT
        PRINT 3080,FP
        PRINT 3090,SHM
        PRINT 3100
        PRINT 3110,TYPROP
        PRINT 3120,TOTCM
```

```
      PRINT 3130,CMIG
      PRINT 3140,CPO
      PRINT 3150,TISO
      PRINT 3160,F
      PRINT 3170,BETA
      PRINT 3180,BXP
      PRINT 3190,FBK
      PRINT 3200,COVOL
      PRINT 3210,GAMA
      PRINT 3220,GNMAS
      PRINT 3230,CD
      PRINT 3240
      PRINT 3250,PA
      PRINT 3260,TA
      PRINT 3270,ROA
      PRINT 3280,SVA
      PRINT 3290
      PRINT 3300,DT
      PRINT 3310,NB
      PRINT 3340
      PRINT 3350
      PRINT 3360,(GRAD(I),BURNA(I),I=1,NTAB)
*****************************************************************
*                                                               *
*     INITIALIZE VARIOUS VARIABLES                              *
*     LOCATE INITIAL GAS BOUNDARIES AND CHARGE SEGMENTS         *
*                                                               *
*****************************************************************
      DT=.0001
      XNB=NB
      TIME=DT
      RG= F/TISO
      SVK=GAMG*32.174*RG
      BA=.7854*BD*BD
      CA=.7854*CHD*CHD
      SHX=CHL
      SHV=0.
      SHA=0.
      CL=CHL/(XNB-1.)
      GMS=TOTCM/((XNB-1.)*GNMAS)
      L=NB-1
      DIST=0.
      DO 10 I=1,L
      X(I)=DIST
      CY(I)=DIST
      DVSUM(I)=0.
 10   DIST=DIST+CL
      X(NB)=CHL
      DO 20 I=1,NB
      DO 20 J=1,4
      IWA(I,J)=1
 20   W(I,J)=0.
*****************************************************************
*                                                               *
*     DETERMINE CONDITIONS AT PSHOT                             *
```

```
*                                                                          *
*   ************************************************************************
      IP=1
      I=1
      N=1
      CMAS(1)=TOTCM/(XNP-1.)
      VOL=12.*CA*X(2)-CMAS(1)/CRO
      GMAS(1)=VOL*ROA+CMIG/(XNB-1.)
      P(1)=12.*GMAS(1)*RG*TISO/(VOL-COVCL*GMAS(1))
      T(1)=TISO
      R(1)=GRAD(1)
      TCMAS(1)=CMAS(1)
      AGV=0.
      ACV=0.
      KTYP=2
      GO TO 200
 30   IF(P(1).GE.PSHOT) GO TO 40
      TIME=TIME+DT
      GO TO 200
 40   L=NP-1
      DO 50 I=1,L
       (I)=P(1)
      V(I)=0.
      RO(I)=RO(1)
      T(I)=TISO
      GMAS(I)=GMAS(1)
      TCMAS(I)=TCMAS(1)
      CMAS(I)=CMAS(1)
      CV(I)=0.
 50   P(I)=P(1)
      OP=P(1)
      I=NP-1
      DT=.00005
      SHA=32.174*(P(NP-1)-FP)*BA/SHM
      SHV=SHA*DT
      SHX=SHX+SHV*SHV/(SHA*2.)
      X(NP)=SHX
      CT=TISO
      BT=TISO
      PV=SHV
      DV=SHV
      DP=-.374*RO(I)*SQRT(SVK*TISO)*DV
      BP=P(I)+DP
      BGMAS=RO(I)*BA*BV*DT*12.
      VOL=(SHX-CHL)*BA*12.
      BRO=BGMAS/VOL
      DM=BGMAS
      VOL=(CHL-X(I))*CA*12.-CMAS(1)/CRO
      CGMAS=GMAS(1)-DM
      CHRO=CGMAS/VOL
      DP=-.374*CHRO*SQRT(SVK*TISO)*DV
      CP=P(I)+DP.
      H(I,1)=-2.68*DP/(RO(1)*SQRT(SVK*TISO))
      IWA(I,1)=0
      CHV=W(I,1)
```

```
      TCMASC=CMAS(1)
      TCMASP=0.
      DVSUM(I)=W(I,1)
      GO TO 400
*************************************************************************
*                                                                       *
*     PROPELLANT BURN SECTION                                           *
*                                                                       *
*************************************************************************
 100  DIST=X(NB)-X(NB-1)
      IF(X(NB-1).LT.CHL.AND.CHL.LT.X(NB)) GO TO 102
      WV=SQRT(SVK*T(NB-1))-V(NB-1)
      DT=2.*DIST/WV
      GO TO 104
 102  WV=SQRT(SVK*(.5*(BT+CT)))-.5*(BV+CHV)
      DT=2.*DIST/WV
 104  TIME = TIME+DT
      IF(NOCH.EQ.2) GO TO 301
      ID=2
      I=1
      N=1
      GO TO 1101
 105  I=I+1
      IF(I.EQ.NB) GO TO 301
      GO TO 1101
 200  GO TO(201,202,203,204,205,206,202,207,202,208,209),KTYP
 201  PRES=.5*(P(I)+P(I-1))
      GO TO 210
 202  PRES=P(I)
      GO TO 210
 203  PRES=.5*(P(I-1)+CP)
      GO TO 210
 204  PRES=.5*(BP+CP)
      GO TO 210
 205  PRES=CP
      GO TO 210
 206  PRES=BP
      GO TO 210
 207  PRES=.5*(BP+P(I))
      GO TO 210
 208  PRES=.5*(CP+P(I))
      GO TO 210
 209  PRES=.5*(P(I-1)+BP)
 210  IF(N.EQ.(NB-1)) CP=PRES
      RDOT=BETA*((PRES/1000.)**BXP)+EBK*(AGV-ACV)
      GRAD=R(N)
      OSURFA=ATKN(GRAD,BURNA,NTAB,1,GRAD)
      R(N)=R(N)-RDOT*DT
      IF(R(N).GE.0.) GO TO 212
      NOCH=1
      GO TO 105
 212  XRAD=R(N)
      SURFA=ATKN(GRAD,BURNA,NTAB,1,XRAD)
      DCM=ABS((GRAD*OSURFA-XRAD*SURFA)*CRC*GNS)
      CMAS(N)=CMAS(N)-DCM
```

```
213   GO TO(214,22),214,214,222,224,220,214,220,216,218),KTYP
2.    DIST=X(I)-CX(N)
      IF(KTYP.EQ.4) DIST=CHL-CX(N)
      IF(ID.EQ.5) GO TO 920
      DML=DCM*DIST/CL
      DMP=DCM-DML
      IF(KTYP.EQ.4) GC TO 215
      L=I-1
215   DM=DML
      M=1
      IF(KTYP.EQ.8) GO TO 240
      IF(KTYP.EQ.4) GO TO 235
      GO TO 230
216   DIST=CHL-CX(N)
      WDIST=X(I)-CHL
      IF(ID.EQ.5) GO TO 920
      DML=DCM*DIST/CL
        DMC=DCM*WDIST/CL
      DMR=DCM-DML-DMC
      L=I-1
      DM=DML
      M=1
      GO TO 235
218   DIST=X(I)-CX(N)
      WDIST=CHL-X(I)
      IF(ID.EQ.5) GO TO 920
      DML=DCM*DIST/CL
      DMC=DCM*WDIST/CL
      DMR=DCM-DML-DMC
      L=I-1
      DM=DML
      M=1
      GO TO 230
220   IF(ID.EQ.5) GO TO 920
      DM=DCM
      L=I
      GO TO 230
222   IF(ID.EQ.5) GO TO 920
      DM=DCM
      L=I
      GO TO 235
224   IF(ID.EQ.5) GO TO 920
      DM=DCM
      L=I
      GO TO 240
230   TCMAS(L)=TCMAS(L)-DM
      XMR=GMAS(L)/(GMAS(L)+DM)
      GMAS(L)=GMAS(L)+DM
      T(L)=TISO*(1.-XMR)+T(L)*XMR
      A=PA
      IF(X(L).LT.CHL.AND.CHL.GE.X(L+1)) A=CA
      VOL=(X(L+1)-X(L))*A*12.-TCMAS(L)/CRC
      RO(L)=GMAS(L)/VOL
      IF(N.EQ.(NR-1).AND.I.LE.(NR-2)) PSTCR=P(I)
      P(L)=12.*GMAS(L)*RG*T(L)/(VOL-COVCL*GMAS(L))
```

```
      IF(IP.EQ.1) GO TO 30
      GO TO 245
 2..  TCMASC=TCMASC-DM
      XMR=CGMAS/(CGMAS+DM)
      CGMAS=CGMAS+DM
      CT=TISO*(1.-XMR)+CT*XMR
      VOL=CA*(CHL-X(L))*12.-(TCMASC/CRO)
      CHPO=CGMAS/VOL
      CP=12.*CGMAS*RG*CT/(VOL-CCVOL*CGMAS)
      GO TO 245
 240  TCMASB=TCMASB-DM
      XMR=BGMAS/(BGMAS+DM)
      BGMAS=BGMAS+DM
      BT=TISO*(1.-XMR)+BT*XMR
      VOL=BA*(X(L+1)-CHL)*12.-(TCMASB/CRO)
      BRO=BGMAS/VOL
      BP=12.*BGMAS*RG*BT/(VOL-CCVOL*BGMAS)
 245  GO TO (250,270,252,254,270,270,270,250,270,256,260),KTYP
 250  IF(M.EQ.2) GO TO 270
      M=2
 251  DM=DMR
      L=I
      GO TO 239
 252  IF(M.EQ.2) GO TO 270
      M=2
      DM=DMR
      L=I
      GO TO 235
 254  IF(M.EQ.2) GO TO 270
      M=2
      DM=DMR
      GO TO 240
 256  IF(M.EQ.3) GO TO 270
      IF(M.EQ.2) GO TO 258
      M=2
      DM=DMC
      GO TO 240
 258  M=3
      GO TO 251
 260  IF(M.EQ.3) GO TO 270
      IF(M.EQ.2) GO TO 262
      M=2
      DM=DMC
      L=I
      GO TO 235
 262  M=3
      DM=DMR
      GO TO 240
 270  IF(ID.EQ.1) GO TO 30
      IF(N.EQ.(NB-1)) GO TO 275
      N=N+1
      GO TO 1101
 275  IF(I.EQ.(NB-1).AND.KTYP.EQ.3.OR.KTYP.EQ.5) GO TO 277
      IF(I.LT.(NB-1)) GO TO 280
      GO TO 301
```

```
 277  DP=CP-OP
      BP=BP+DP
      GO TO 301
 280  TAV=DT
      IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 288
      DP=P(I)-OP
 282  I=I+1
      IF(I.EQ.NP) GO TO 301
      IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 292
 284  K=I+1
      SV=SQRT(SVK*T(I))
      WV=SV+V(I)
      DIST=X(K)-X(I)
      TTC=DIST/WV
      IF(TTC.GT.TAV) GO TO 301
      TAV=TAV-TTC
      P(I)=P(I)+DP
      GO TO 282
 288  IF(KTYP.EQ.3.OR.KTYP.EQ.5) GO TO 290
      DP=BP-OP
      I=I+1
      GO TO 284
 290  DP=CP-OP
      BP=BP+DP
      I=I+1
      GO TO 284
 292  K=I+1
      SV=SQRT(SVK*(.5*(BT+CT)))
      WV=SV+.5*(CHV+BV)
      DIST=X(K)-X(I)
      TTC=DIST/WV
      IF(TTC.GT.TAV) GO TO 301
      TAV=TAV-TTC
      CP=CP+DP
      BP=BP+DP
      GO TO 282
***********************************************************************
*                                                                     *
*     SHELL MOTION SECTION                                            *
*                                                                     *
***********************************************************************
 301  OSHV=SHV
      PRES=.5*(P(NP-1)+OP)
      IF(X(NP-1).LT.CHL) PRES=.5*(BP+OP)
      ADP=PA*(1.+ GAMA*OSHV/(2.*SVA)*((GAMA+1.)*OSHV/(2.*SVA)+SQRT(((GAM
     1A+1.)*OSHV/(2.*SVA))**2.+4.)))
      SHA=32.174*(PRES-ADP-FP)*BA/SHM
      SHV=OSHV+SHA*DT
      SHX=SHX+SHV*SHV/(SHA*2.)
      IF(SHX.GE.GUNL) GO TO 1500
      X(NP)=SHX
      W(NP,1)=W(NP,1)+(SHV-OSHV)
      IWA(NP,1)=0
***********************************************************************
*                                                                     *
```

```
*      WAVE PROPOGATION SECTION                                          *
                                                                         *
**************************************************************************
 400  I=2
      J=1
      IX=0
 410  IF(IWA(I,J).EQ.0) GO TO 470
      IF(J.EQ.2.OR.J.EQ.4) GO TO 420
      IF(I.EQ.NP) GO TO 430
      I=I+1
      GO TO 410
 420  IF(I.EQ.1) GO TO 430
      I=I-1
      GO TO 410
 430  GO TO (440,450,460,590),J
 440  J=2
      I=NP-1
      GO TO 410
 450  J=3
      I=2
      GO TO 410
 460  J=4
      I=NP-1
      GO TO 410
 470  DV=W(I,J)
      IF(KCHW.EQ.1.OR.KCHW.EQ.2) GO TO 471
      IS=I
      JS=J
      TAV=DT
 471  IF(J.EQ.2.OR.J.EQ.4) GO TO 475
      IF(X(I-1).LT.CHL.AND.CHL.LT.X(I)) GO TO 500
      K=I-1
      SV=SQRT(SVK*T(K))
      WV=SV-V(K)
      IF(WV.LT.0.) GO TO 496
      DIST=X(I)-X(K)
      GO TO 480
 475  IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 500
      K=I+1
      SV=SQRT(SVK*T(I))
      WV=SV+V(I)
      DIST=X(K)-X(I)
 480  TTC=DIST/WV
      IF(TTC.GT.TAV) GO TO 495
 481  IWA(I,J)=1
      W(I,J)=0.
      TAV=TAV-TTC
      IF(J.EQ.1.OR.J.EQ.3) I=I-1
        DP=-.373*RO(I)*SQRT(SVK*T(I))*DV
        P(I)=P(I)+DP
      DVSUM(I)=DVSUM(I)+DV
      IF(J.EQ.2.OR.J.EQ.4) I=I+1
      IWA(I,J)=0.
      W(I,J)=W(I,J)+DV
      IF(I.EQ.1) GO TO 485
```

RUN

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```
      IF(I.EQ.NP) GO TO 490
      IF(IX.EQ.1) GO TO 482
      GO TO 471
  482 IX=0
      IWA(I,J)=2
      W(I,J)=DV
      I=IS
      J=JS
      GO TO 410
  485 IWA(I,J)=1
      W(I,J)=0.
      IF(J.EQ.1) J=2
      IF(J.EQ.3) J=4
      IWA(I,J)=0
      W(I,J)=W(I,J)+DV
      IF(IX.EQ.1) GO TO 486
      GO TO 471
  486 IX=0
      IWA(I,J)=2
      I=IS
      J=JS
      GO TO 410
  490 IWA(I,J)=1
      W(I,J)=0.
      IF(J.EQ.2) J=1
      IF(J.EQ.4) J=3
      IWA(I,J)=0
      W I,J)=W(I,J)+DV
      IF(IX.EQ.1) GO TO 491
      GO TO 471
  491 IX=0
      IWA(I,J)=2
      I=IS
      J=JS
      GO TO 410
  495 IF(KCHW.EQ.1) GO TO 498
      IF(KCHW.EQ.2) GO TO 499
      WDIST=WV*TAV
      IF(WDIST.GT.(.5*DIST)) GO TO 497
  496 IWA(I,J)=2
      W(I,J)=DV
      I=IS
      J=JS
      GO TO 410
  497 IX=1
      GO TO 431
  498 IWA(I,J)=2
      W(I,J)=DV
      I=IP
      J=JP
      DV=DVB+W(I,J)
      KCHW=2
      IWA(I,J)=0
      TAV=TAC
      IF(I.EQ.NB) GO TO 490
```

```
      GO TO 470
 ]°   KCHW=0
      GO TO 496
50.   IF(KCHW.EQ.1) GO TO 4(
      IF(KCHW.EQ.2) GO TO 4'
      IF(J.EQ.2.OR.J.EQ.4)      G 505
      K=I-1
      SV=.5*(SQRT(SVK*CT)+
      WV=SV-.5*(BV+CHV)
      IF(WV.LT.0.) GO TO
      DIST=X(I)-X(K)
      GO TO 507
505   K=I+1
      SV=.5*(SQRT(SVK*CT)    T(SVK
      WV=SV+.5*(BV+CHV)
      IF(WV.LT.0.) GO TO
      DIST=X(K)-X(I)
507   TTC=DIST/WV
      IF(TTC.GT.TAV) GO TO 496
      TAV=TAV-TTC
      TAC=TAV
      IWA(I,J)=1
      W(I,J)=0.
      L=I
      IF(J.EQ.1.OR.J.EQ.3) L=I-1
      BV=BV+DV
      DM=CHRO*BA*BV*DI*12.
      BGMAS=BGMAS+DM
      CGMAS=CGMAS-DM
      OBP=BP
      OCP=CP
      VOL=(X(L+1)-CHL)*BA*12.-TCMASP/CRO
      BP=12.*BGMAS*RG*BT/(VOL-COVOL*BGMAS)
      BRO=BGMAS/VOL
      DVB=-2.683*(BP-OBP)/(BRO*SQRT(SVK*BT))
      VOL=(CHL-X(L))*CA*12.-TCMASC/CRO
      CP=12.*CGMAS*RG*CT/(VOL-COVOL*CGMAS)
      CHRO=CGMAS/VOL
      DVC=-2.683*(CP-OCP)/(CHRO*SQRT(SVK*CT))
      JB=2
      IF(DVB.LT.0.) JB=4
      JC=1
      IF(DVC.LT.0.) JC=3
      IF(J.EQ.1.OR.J.EQ.3) GO TO 581
      DVSUM(I)=DVSUM(I)+DVC
      DVSUM(I+1)=DVSUM(I+1)+DVB
      IB=I+1
      GO TO 582
581   IB=I
      DVSUM(I)=DVSUM(I)+DVB
      DVSUM(I-1)=DVSUM(I-1)+DVC
      I=I-1
5..   KCHW=1
      J=JC
      IWA(I,J)=0
```

```
      W(I,J)=W(I,J)+DVC
      TAV=TAC
      GC TO 471
 593  DO 595 I=1,NR
      DO 595 J=1,4
 595  IF(IWA(I,J).EQ.2) IWA(I,J)=0
*************************************************************************
*                                                                       *
*     CHARGE MOTION SECTION                                             *
*                                                                       *
*************************************************************************
      IF(NOCH.EQ.2) GO TO 801
      ID=3
      I=1
      N=1
      GO TO 1101
 615  I=I+1
      IF(I.EQ.NR) GO TO 801
      GC TO 1101
 620  GO TO (625,630,635,640,645,650,630,655,630,660,665),KTYP
 625  AGV=.5*(V(I-1)+V(I))
      GO TO 670
 630  AGV=V(I)
      GC TO 670
 635  AGV=.5*(V(I-1)+CHV)
      GC TO 670
    ^ AGV=.5*(PV+CHV)
      GC TO 670
 645  AGV=CHV
      GC TO 670
 650  AGV=PV
      GC TO 670
 655  AGV=.5*(PV+V(I))
      GO TO 670
 660  AGV=.5*(CHV+V(I))
      GO TO 670
 665  AGV=.5*(V(I-1)+PV)
 670  IF(NOCH.EQ.2) GC TO 672
      ACV=CV(N)
      IF(ACV.LE.0.) AGV=C.
 672  IF(AGV.LE.0.) AGV=0.
      IF(ID.EQ.2) GO TO 200
      GO TO (675,680,700,705,720,725,730,735,740,745,750),KTYP
 675  PDIF=P(I-1)-P(I)
      AGRO=.5*(RC(I-1)+RO(I))
      GO TO 755
 680  IF(I.EQ.1) GO TO 690
      IF(I.EQ.(NR-1)) GC TO 695
      PDIF=P(I-1)-P(I+1)
 685  AGRO=RO(I)
      GC TO 755
 69^  PDIF=P(1)-P(2)
      GO TO 685
 695  PDIF=P(NR-1)-P(I)
      GO TO 685
```

```
 7.0  PDIF=P(I-1)-BP
      AGRO=.5*(RO(I-1)+CHRO)
      GO TO 755
 705  IF(I.EQ.(NP-1)) GO TO 715
      PDIF=.5*(P(I-1)-P(I+1))
 710  AGRO=.5*(PRO+CHRO)
      GO TO 755
 715  PDIF=P(I-1)-.5*(BP+CP)
      GO TO 710
 720  PDIF=P(I-1)-BP
      AGRO=CHRO
      GO TO 755
 725  PDIF=CP-P(I+1)
      AGRO=PRO
      GO TO 755
 730  PDIF=P(I-1)-CP
      AGRO=RO(I)
      GO TO 755
 735  PDIF=CP-P(I)
      AGRO=.5*(RO(I)+BRO)
      GO TO 755
 740  PDIF=PP-P(I+1)
      AGRO=PO(I)
      GO TO 755
 745  PDIF=CP-P(I)
      AGRO=.5*(CHRO+RO(I))
      GO TO 755
 750  PDIF=P(I-1)-BP
      AGRO=.5*(PO(I-1)+PRO)
 755  A1=CMAS(N)/(CRO*CL*12.)
      CV(N)=CV(N)+(DT/CMAS(N))*(PDIF*A1*32.174+.5*AGRO*A1*CC*(AGV*AGV-2.
     1*CV(N)*AGV+CV(N)*CV(N)))
      IF(CV(N).LE.0.) CV(N)=0.
      CX(N)=CX(N)+CV(N)*DT
      IF(N.EQ.(NB-1)) GO TO 801
      N=N+1
      GO TO 1101
****************************************************************************
*                                                                          *
*     GAS BOUNDARY MOTION SECTION                                          *
*                                                                          *
****************************************************************************
 801  I=2
 805  IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 810
      V(I)=DVSUM(I)
      X(I)=X(I)+V(I)*DT
      A=PA
      IF(X(I).LT.CHL)A=CA
      DM=12.*RO(I)*A*V(I)*DT
      GMAS(I-1)=GMAS(I-1)+DM
      GMAS(I)=GMAS(I)-DM
 807  IF(I.EQ.(NP-1)) GO TO 901
      I=I+1
      GO TO 805
 810  DIST=CHL-X(I)
```

```
      TTC=DIST/CHV
      IF(TTC.GT.DT) GO TO 920
      TAV=DT-TTC
      A=BGMAS+CGMAS
      X(I)=CHL+BV*DT
      DVSUM(I)=BV
      DM=12.*CHRO*CA*CHV*DT
      GMAS(I)=A-DM
      CGMAS=GMAS(I-1)+DM
      DM=12.*BRO*BA*BV*DT
      BGMAS=DM
      GMAS(I)=GMAS(I)-DM
      GO TO 837
 920  X(I)=X(I)+CHV*DT
      DVSUM(I)=CHV
      DM=12.*RO(I-1)*CA*CHV*DT
      GMAS(I-1)=GMAS(I-1)+DM
      CGMAS=CGMAS-DM
      I=I+1
      IF(I.EQ.NR) GO TO 901
      X(I)=X(I)+BV*DT
      DVSUM(I)=BV
      DM=12.*RO(I)*BA*BV*DT
      BGMAS=BGMAS+DM
      GMAS(I)=GMAS(I)-DM
      GO TO 837
 ***********************************************************************
*                                                                      *
*     CHARGE REDISTRIBUTION SECTION                                    *
*                                                                      *
************************************************************************
 901  IR=5
      IF(NOCH.EQ.2) GO TO 1300
      L=NR-1
      DO 910 N=1,L
      IF(R(N).GE.0.) GO TO 915
 910  CONTINUE
      NOCH=2
      GO TO 1301
 915  L=NR-1
      DO 916 I=1,L
 916  TCMAS(I)=0.
      TCMASC=0.
      TCMASB=0.
      I=1
      N=1
      GO TO 1101
 918  IF(I.EQ.(NR-1)) GO TO 935
      I=I+1
      GO TO 1101
 920  GO TO(921,922,923,924,925,926,922,928,922,930,931),KTYP
 921  TCMAS(I-1)=TCMAS(I-1)+CMAS(N)*DIST/CL
      TCMAS(I)=TCMAS(I)+CMAS(N)*(CL-DIST)/CL
      GO TO 935
 922  TCMAS(I)=TCMAS(I)+CMAS(N)
```

```
      GO TO 935
 923  TCMAS(I-1)=TCMAS(I-1)+CMAS(N)*DIST/CL
      TCMASC=TCMASC+CMAS(N)*(CL-DIST)/CL
      GO TO 935
 924  TCMASC=TCMASC+CMAS(N)*DIST/CL
      TCMASB=TCMASB+CMAS(N)*(CL-DIST)/CL
      GO TO 935
 925  TCMASC=TCMASC+CMAS(N)
      GO TO 935
 926  TCMASB=TCMASB+CMAS(N)
      GO TO 935
 928  TCMASB=TCMASB+CMAS(N)*DIST/CL
      TCMAS(I)=TCMAS(I)+CMAS(N)*(CL-DIST)/CL
      GO TO 935
 930  TCMASC=TCMASC+CMAS(N)*DIST/CL
      TCMASB=TCMASB+CMAS(N)*WDIST/CL
      TCMAS(I)=TCMAS(I)+CMAS(N)*(CL-DIST-WDIST)/CL
      GO TO 935
 931  TCMAS(I-1)=TCMAS(I-1)+CMAS(N)*DIST/CL
      TCMASC=TCMASC+CMAS(N)*WDIST/CL
      TCMASB=TCMASB+CMAS(N)*(CL-DIST-WDIST)/CL
 935  IF(N.EQ.(NB-1)) GO TO 1000
      N=N+1
      GO TO 1101
******************************************************************
*                                                                *
*     GAS PROPERTY REALIGNMENT SECTION                           *
*                                                                *
******************************************************************
 1000 L=NB-1
      DO 1030 I=1,L
      IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 1020
      A=BA
      IF(X(I).LT.CHL) A=CA
      VOL=(X(I+1)-X(I))*A*12.-(TCMAS(I)/CRO)
      RO(I)=GMAS(I)/VOL
      T(I)=P(I)*(VOL-GMAS(I)*COVOL)/(12.*GMAS(I)*RG)
      GO TO 1030
 1020 VOL=(CHL-X(I))*CA*12.-(TCMASC/CRO)
      CHRO=CGMAS/VOL
      CT=CP*(VOL-CGMAS*COVOL)/(12.*CGMAS*RG)
      VOL=(X(I+1)-CHL)*BA*12.-(TCMASB/CRO)
      BRO=BGMAS/VOL
      BT=BP*(VOL-BGMAS*COVOL)/(12.*BGMAS*RG)
 1030 CONTINUE
      GO TO 1301
******************************************************************
*                                                                *
*     CHARGE LOCATION SECTION                                    *
*                                                                *
******************************************************************
 1101 LTYP=0
      IF(P(N).GE.0.) GO TO 1105
      NOCH=1
      GO TO (100,105,615,620,918),IO
```

```
1105 IF(I.EQ.NB) GO TO 1110
     IF(CX(N).GE.X(I).AND.(CX(N)+CL).LE.X(I+1)) GO TO 1130
     IF(CX(N).LT.X(I).AND.X(I).LT.(CX(N)+CL))GO TO 1115
1110 NOCH=1
     GO TO (100,105,615,620,918),ID
1115 LTYP=1
1130 NOCH=0
     IF(LTYP.EQ.1) GO TO 1135
     IF(I.LE.2.OR.I.GE.(NB-1)) GO TO 1135
     IF(X(I).LT.CHL.A...,X(I+2).LT.CHL) GO TO 1145
     IF(X(I-2).GT.CHL) GO TO 1145
1135 IF(X(I).LT.CHL.AND.CHL.LT.X(I+1)) GO TO 1150
     IF(I.EQ.(NB-1)) GO TO 1140
     IF(X(I+1).LT.CHL.AND.CHL.LT.X(I+2)) GO TO 1160
     IF(I.EQ.1) GO TO 1145
1140 IF(X(I-1).LT.CHL.AND.CHL.LT.X(I)) GO TO 1170
1145 KTYP=2
     IF(LTYP.EQ.1)KTYP=1
     GO TO 1180
1150 IF(LTYP.EQ.0) GO TO 1155
     KTYP=3
     IF(CX(N).LT.X(I).AND.(CX(N)+CL).GT.CHL) KTYP=11
     GO TO 1180
1155 KTYP=4
     IF(NOCH.EQ.2) GO TO 1180
     IF(ID.EQ.4) GO TO 1180
     IF(CX(N).GE.X(I).AND.(CX(N)+CL).LE.CHL) KTYP=5
     IF(CX(N).GE.CHL.AND.(CX(N)+CL).LE.X(I+1))KTYP=6
     GO TO 1180
1160 IF(LTYP.EQ.1) GO TO 1165
     KTYP=7
     GO TO 1180
1165 KTYP=1
     GO TO 1180
1170 IF(LTYP.EQ.1) GO TO 1175
     KTYP=9
     GO TO 1180
1175 KTYP=8
     IF(NOCH.EQ.2) GO TO 1180
     IF(CX(N).LT.CHL.AND.(CX(N)+CL).GT.X(I)) KTYP=10
1180 GO TO (100,620,620,620,213),ID
************************************************************************
*                                                                      *
*      OUTPUT                                                          *
*                                                                      *
************************************************************************
 1301 PRINT 3500,TIME
      PRINT 3510,SHX
      PRINT 3520,SHV
      PRINT 3530,SHA
      PRINT 3540
      PRINT 3545.
      L=NB-1
      DO 1320 I=1,L
      IF(I.EQ.(NB-1).AND.X(I).LT.CHL) GO TO 1310
```

```
      PRES=P(I)
      OP=PRES
      VEL=V(I)
      ROW=RO(I)
      TEMP=T(I)
      CMASS=TCMAS(I)
      POS=X(I)
      GO TO 1320
 1310 PRES=PP
      OP=PRES
      VEL=PV
      ROW=PRO
      TEMP=PT
      CMASS=TCMASB
      POS=X(I)
 1320 PRINT 3550,POS,PRES,VEL,TEMP,ROW,CMASS
*************************************************************************
*                                                                       *
*      RETURN TO PRESSURE BURN TO RESTART CYCLE                         *
*                                                                       *
*************************************************************************
      GO TO 100
 1500 CONTINUE
*************************************************************************
*                                                                       *
*      FORMATS                                                          *
*                                                                       *
*************************************************************************
 2000 FORMAT(A10,A10)
 2001 FORMAT(4E15.4)
 2002 FORMAT(I2,I3)
 2003 FORMAT(2E10.4)
 3000 FORMAT(1H1,*GUN DESCRIPTION*//)
 3010 FORMAT(1H ,*TYPE OF GUN*,T30,A17)
 3020 FORMAT(1H ,*GUN LENGTH*,T30,F13.5,T50,*FT*)
 3030 FORMAT(1H ,*CHAMBER LENGTH*,T30,F13.5,T50,*FT*)
 3040 FORMAT(1H ,*CHAMBER DIAMETER*,T30,F13.5,T50,*IN*)
 3050 FORMAT(1H ,*BORE DIAMETER*,T30,F13.5,T50,*IN*//)
 3060 FORMAT(1H ,*GUN AND SHELL INFORMATION*/)
 3070 FORMAT(1H ,*SHELL START PRESSURE*,T30,F13.5,T50,*LBF/SQ IN*)
 3080 FORMAT(1H ,*GUN FRICTION PRESSURE*,T30,F13.5,T50,*LBF/SQ IN*)
 3090 FORMAT(1H ,*SHELL MASS*,T30,F13.5,T50,*LBM*//)
 3100 FORMAT(1H ,*PROPELLANT INFORMATION*/)
 3110 FORMAT(1H ,*TYPE OF PROPELLANT*,T30,A13)
 3120 FORMAT(1H ,*PROPELLANT MASS*,T30,F13.5,T50,*LBM*)
 3130 FORMAT(1H ,*IGNITER MASS*,T30,F13.5,T50,*LBM*)
 3140 FORMAT(1H ,*PROPELLANT DENSITY*,T30,F13.5,T50,*LBM/CUBIC IN*)
 3150 FORMAT(1H ,*ISOCHORIC FLAME TEMP*,T30,F13.5,T50,*DEG R*)
 3160 FORMAT(1H ,*FORCE CONSTANT*,T30,F13.5,T50,*FT-LBF/LBM*)
 3170 FORMAT(1H ,*PRESSURE BURN RATE COEF*,T30,F13.5,T50,*IN/SEC-1000 PS
     1I*)
 31   FORMAT(1H ,*PRESSURE BURN RATE EXPONENT*,T30,F13.5)
 31   FORMAT(1H ,*EROSIVE BURN RATE COEF*,T30,F13.5)
 3200 FORMAT(1H ,*COVOLUME*,T30,F13.5,T50,*CUBIC IN/LBM*)
 3210 FORMAT(1H ,*RATIO OF SPECIFIC HEATS*,T30,F13.5)
```

```
3220 FORMAT(1H ,*MASS PER GRAIN*,T30,F13.5,T50,*LBM*)
3230 FORMAT(1H ,*DRAG COEF*,T30,F13.5//)
3240 FORMAT(1H ,*ATMOSPHERIC CONDITIONS*/)
3250 FORMAT(1H ,*PRESSURE*,T30,F13.5,T50,*LBF/SQ IN*)
3260 FORMAT(1H ,*TEMPERATURE*,T30,F13.5,T50,*DEG R*)
3270 FORMAT(1H ,*DENSITY*,T30,F13.5,T50,*LBM/CUBIC IN*)
3280 FORMAT(1H ,*SONIC VELOCITY*,T30,F13.5,T50,*FT/SEC*//)
3290 FORMAT(1H ,*PROBLEM VARIABLES*/)
3300 FORMAT(1H ,*TIME INCREMENT*,T30,F13.5,T50,*SEC*)
3310 FORMAT(1H ,*NUMBER OF GAS BOUNDARIES*,T30,I13)
3340 FORMAT(1H1,*PROPELLANT GRAIN BURN DISTANCE VS SURFACE AREA*//)
3350 FORMAT(1H ,*BURN DIST (IN)*,T37,*SURFACE AREA (SQ IN)*//)
3360 FORMAT(1H ,F13.5,T44,F13.5)
3500 FORMAT(1H1,*TIME*,T32,F10.6,T50,*SEC*)
3510 FORMAT(1H ,*SHELL POSITION*,T32,F13.4,T50,*FT*)
3520 FORMAT(1H ,*SHELL VELOCITY*,T32,F10.4,T50,*FT/SEC*)
3530 FORMAT(1H ,*SHELL ACCELERATION*,T32,F10.2,T50,*FT/SQ SEC*///)
3540 FORMAT(1H ,2X,*POSITION*,T18,*PRESSURE*,T33,*VELOCITY*,T45,*TEMPER
    1ATURE*,T64,*DENSITY*,T77,*PROP MASS*)
3545 FORMAT(1H ,6X,*(FT)*,T15,*(LBF/SQ IN)*,T33,*(FT/SEC)*,T50,*(DEG R
    1)*,T59,*(LBM/CUB IN)*,T81,*(LBM)*//)
3550 FORMAT(1H ,F10.4,T16,F10.2,T31,F10.2,T46,F10.2,T61,F10.7,T76,F10.
    14)
************************************************************************
      END
```

CDC 6600 FTN V3.0-279C OPT=1 02/07/72

```
*DECK ATKN
      FUNCTION ATKN(X,Y,N,K,XI)
C
C     ATKN     AITKEN INTERPOLATING FUNCTION
C
C     USAGE...
C
C     Z=ATKN(X,Y,N,K,XI)
C
C        WHERE...
C
C        X - TABLE OF INDEPENDENT VARIABLE VALUES,
C            (MAY BE ASCENDING OR DESCENDING).
C        Y - TABLE OF DEPENDENT VARIABLE VALUES.
C        N - NO. OF POINTS IN TABLES X AND Y.
C        K - DEGREE OF INTERPOLATION DESIRED.
C        XI- X-VALUE FOR WHICH INTERPOLATION IS DESIRED.
C
C        THE INTEPOLATED VALUE IS RETURNED AS THE FUNCTION VALUE.
C
C        31 CELLS OF BLANK COMMON ARE USED.
C
      DIMENSION   X(N), Y(N)
      COMMON   I1, K1, LI, LL, LU
      COMMON   XX(13), YY(13)
      DATA   KMAX/ 12/

      IF ( K .GT. KMAX .OR. K .LE. 0 )     GO TO 300
C
      K1=K+1
      IF (X(N)-X(1)) 100,10,10
   10 IF (XI-X(1)) 20,20,30
   20 LL=1
      GO TO 200
   30 IF (X(N)-XI) 40,40,50
   40 LL=N-K1
      GO TO 200
   50 LI=1
      LU=N
   60 IF (LU-LL-1) 180,180,70
   70 LI=(LL+LU)/2
      IF (X(LI)-XI) 80,80,90
   80 LL=LI
      GO TO 60
   90 LU=LI
      GO TO 60
  100 IF (XI-X(1)) 120,20,20
  120 IF (X(N)-XI) 130,40,40
  130 LL=1
      LU=N
  140 IF (LU-LL-1) 180,180,150
  150 LI=(LL+LU)/2
      IF (X(LI)-XI) 160,170,170
  160 LL=LT
      GO TO 140
```

ATKN CDC 6600 FTN V3.0-279C OPT=1 02/07/72 1

```
 70 LL=LI
    GO TO 140
180 LL=LL-(K1+1)/2
    IF (LL) 20,200,190
190 IF (LL+K1-N) 200,200,40
200 DO 210 I=1,K1
    I1=LL+I
    XY(I)=X(I1)-XI
210 YY(I)=Y(I1)
    DO 220 I=1,K
    DO 220 J=I,K
220 YY(J+1)=(1./(XX(J+1)-XX(I)))*(YY(I)*XX(J+1)-YY(J+1)*XX(I))
    ATKN=YY(K1)
    RETURN
C
500  PRINT 1000, K
1000 FORMAT (3H0K=,I12,33H   IS INCORRECT FOR FUNCTION ATKN)
    CALL SYSTEM(200,0)
    END
```

GUN DESCRIPTION

TYPE OF GUN	155MM HOW	
GUN LENGTH	18.30000	FT
CHAMBER LENGTH	2.43000	FT
CHAMBER DIAMETER	5.00000	IN
BORE DIAMETER	4.18400	IN

GUN AND SHELL INFORMATION

SHELL START PRESSURE	4000.00000	LBF/SQ IN
GUN FRICTION PRESSURE	350.00000	LBF/SQ IN
SHELL MASS	12.77000	LBM

PROPELLANT INFORMATION

TYPE OF PROPELLANT	NC 11.05	
PROPELLANT MASS	12.15000	LBM
IGNITER MASS	.07260	LBM
PROPELLANT DENSITY	.05750	LBM/CUBIC IN
ISOCHORIC FLAME TEMP	3000.00000	DEG R
FORCE CONSTANT	364500.00000	FT-LBF/LBM
PRESSURE BURN RATE COEF	.49100	IN/SEC-1000 PSI
PRESSURE BURN RATE EXPONENT	.67000	
EROSIVE BURN RATE COEF	.00019	
COVOLUME	29.62000	CUBIC IN/LBM
RATIO OF SPECIFIC HEATS	1.40000	
MASS PER GRAIN	.00214	LBM
DRAG COEF	.10000	

ATMOSPHERIC CONDITIONS

PRESSURE	14.70000	LBF/SQ IN
TEMPERATURE	530.00000	DEG R
DENSITY	.00004	LBM/CUBIC IN
SONIC VELOCITY	1128.55231	FT/SEC

PROBLEM VARIABLES

TIME INCREMENT	.00001	SEC
NUMBER OF GAS BOUNDARIES	21	

PROPELLANT GRAIN BURN DISTANCE VS SURFACE AREA

BURN DIST (IN)	SURFACE AREA (SQ IN)
.03650	1.17700
.03150	1.26700
.02550	1.37000
.01950	1.46500
.01370	1.54800
.01280	1.65000
.01190	.87950
.01080	.72570
.00990	.59960
.00890	.48830
.00790	.35860
.00690	.32950
.00600	.27860
.00500	.22490
.00400	.17810
.00310	.13770
.00210	.09130
.00110	.04590
0.00000	0.00000

TIME	.001710	SEC
SHELL POSITION	2.4332	FT
SHELL VELOCITY	6.6237	FT/SEC
SHELL ACCELERATION	132473.83	FT/SQ SEC

POSITION (FT)	PRESSURE (LBF/SQ IN)	VELOCITY (FT/SEC)	TEMPERATURE (DEG R)	DENSITY (LBM/CUB IN)	PROJ MASS (LBM)
0.0000	4174.21	0.00	3000.00	.0009281	.5954
.1215	4174.21	0.00	3000.00	.0009281	.5954
.2430	4174.21	0.00	3000.00	.0009281	.5954
.3645	4174.21	0.00	3000.00	.0009281	.5954
.4860	4174.21	0.00	3000.00	.0009281	.5954
.6075	4174.21	0.00	3000.00	.0009281	.5954
.7290	4174.21	0.00	3000.00	.0009281	.5954
.8505	4174.21	0.00	3000.00	.0009281	.5954
.9720	4174.21	0.00	3000.00	.0009281	.5954
1.0935	4174.21	0.00	3000.00	.0009281	.5954
1.2150	4174.21	0.00	3000.00	.0009281	.5954
1.3365	4174.21	0.00	3000.00	.0009281	.5954
1.4580	4174.21	0.00	3000.00	.0009281	.5954
1.5795	4174.21	0.00	3000.00	.0009281	.5954
1.7010	4174.21	0.00	3000.00	.0009281	.5954
1.8225	4174.21	0.00	3000.00	.0009281	.5954
1.9440	4174.21	0.00	2995.38	.0009295	.5989
2.0658	4165.48	6.62	2993.60	.0009281	.5954
2.1373	4165.48	6.62	2993.73	.0009281	.5954
2.3388	4165.45	6.62	1454.40	.0019567	.0000

TIME	.001774	SEC
SHELL POSITION	2.4312	FT
SHELL VELOCITY	16.5959	FT/SEC
SHELL ACCELERATION	133597.66	FT/SQ SEC

POSITION (FT)	PRESSURE (LBF/SQ IN)	VELOCITY (FT/SEC)	TEMPERATURE (DEG R)	DENSITY (LBM/CUB IN)	PROF MASS (LBM)
0.0000	4394.95	0.00	3000.00	.0009757	.5945
.1215	4394.95	0.00	3000.00	.0009757	.5945
.2430	4394.95	0.00	3000.00	.0009757	.5945
.3645	4394.95	0.00	3000.00	.0009757	.5945
.4860	4394.95	0.00	3000.00	.0009757	.5945
.6075	4394.95	0.00	3000.00	.0009757	.5945
.7290	4394.95	0.00	3000.00	.0009757	.5945
.8505	4394.95	0.00	3000.00	.0009757	.5945
.9720	4394.95	0.00	3000.00	.0009757	.5945
1.0935	4394.95	0.00	3000.00	.0009757	.5945
1.2150	4394.95	0.00	3000.00	.0009757	.5945
1.3365	4394.95	0.00	3000.00	.0009757	.5945
1.4580	4394.95	0.00	3000.00	.0009757	.5945
1.5795	4394.95	0.00	3000.00	.0009757	.5945
1.7010	4394.95	0.00	2993.23	.0009779	.5968
1.8230	4385.77	6.62	2993.60	.0009758	.5945
1.9445	4385.75	6.62	2989.24	.0009772	.5961
2.0663	4355.08	6.62	2957.90	.0009882	.6072
2.1935	4379.44	43.14	3069.70	.0009608	.5777
2.3093	2778.[illegible]	16.51	1454.43	.0012611	0.0000

Appendix E

Glossary

Glossary

Bore	The interior of the gun barrel. In this work the portion of the barrel from the area change at the chamber to the barrel exit.
Breech	The end of the barrel opposite from the barrel exit.
Chamber	A short length of barrel at the breech end with a larger diameter than the rest of the barrel.
Chambrage	A term referring to the presence of a chamber, as in "a gun with chambrage".
Erosive Burn	Propellant burn induced by the relative velocity of gas past the propellant surface.
Force Constant	Term used in the gun business as a measure of propellant energy potential. The force constant is the product of the propellant gas constant and the isochoric flame temperature.
Isochoric Flame Temperature	Temperature attained if a given mass of propellant is burned adiabatically in a constant-volume container.
Muzzle	The exit end of the barrel.
Propellant grain	Small geometrically-shaped mass of propellant. A commonly-used shape is a cylinder with seven holes aligned with the axis of rotation of the cylinder.
Rifling	A groove machined into the bore to induce a stabilizing spin to the projectile.
Shot Pressure	An artificial pressure used in some analyses (including this one). The projectile is not permitted to move until the shot pressure is attained; this is an approximation to the force necessary to overcome certain frictional resistances to projectile motion.

Vita

Captain James F. Setchell was born in Colorado Springs, Colorado, on 1 February 1943. He received a bachelor of science degree in aerospace engineering from Texas A&M University in May, 1964, and was commissioned a second lieutenant in the United States Air Force at that time. Prior to entry on active duty Captain Setchell was employed as a structural repair engineer for the B-58 Hustler aircraft at the San Antonio Air Materiel Area, San Antonio, Texas. He entered active duty in September, 1964, and from that time until May, 1970, he was assigned to the Strategic Air Command in the missile operations field. Captain Setchell reported to the Air Force Institute of Technology at Wright-Patterson Air Force Base, Ohio, in June, 1970, where he was enrolled in the Graduate Aero-Mechanical School. He completed the course requirements for a master's degree in mechanical engineering in December, 1971, and is currently assigned to the Foreign Technology Division at Wright-Patterson Air Force Base. Captain Setchell is married and has one daughter.

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